PHASED DEVELOPMENTS IN FMS UNDER THE STOCHASTIC ENVIRONMENT

THESIS

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BY

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I Wasif Ullah Khan, Department of Mechanical Engineering certify that the work embodied in this Ph.D. thesis is my own bonafied work carried out by me under the supervision of **Prof. Mohammed Ali** at Aligarh Muslim University, Aligarh. The matter embodied in this Ph.D. thesis has not been submitted for the award of any other degree.

I declare that I have faithfully acknowledge, given credit to and referred to the researchers wherever their works have been cited in the text and the body of the thesis. I further certify that I have not willfully lifted up some other's work, paragraph, text, data, results, etc. or available at web-sites and included them in this Ph.D. thesis and cited as my own work.

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Abstract

In the present age, the manufacturing organizations are facing many unpredictable market changes like technological advancement, shortened product life cycles, intense pressure from competitors and ever growing customers' expectation. To sustain in such an environment the system needs to be responsive and flexible. The flexibility in manufacturing possesses a major challenge in effective integration of different components of the manufacturing system like material flow, information flow and decisions flow etc.

This thesis is aimed to enrich a research theme, focused on exploiting the design, planning and control decisions in an FMS under stochastic environment with a view to improve the performance measures like make-span, work-in-process and resource utilization of an FMS.

In the designing of Stochastic Flexible Manufacturing System (SFMS) in the domain of FMS we assume a fully automated decision system that is capable of making decision in real time perspective. It is useful to view SFMS in terms of three types of decisions, which control its development over any time sphere as a discrete event system. There are events related to the starting and finishing of information, decision and the physical related activities. Here we developed the conceptual framework of the SFMS in phased manner under design, planning and control decisions.

The SFMS comprises of 6 flexible machines M1, M2, M3, M4, M5 and M6 along with the dedicated input buffers. This system manufactures 6 part types each of 100 parts. Hence the total output of the system is 600 parts. Five operations were considered for each part. The operation time is taken from the real manufacturing system under four

different load conditions i.e. UBL, FBL, BMTUPT and UMTBPT. Four levels of sequencing flexibility (i.e. SF0, SF1, SF2 and SF3) and routing flexibility (i.e. RF0, RF1, RF2 and RF3) with four parts sequencing rules (i.e. FCFS, SPT, HPT and LCFS) were considered for the study.

The simulation model of SFMS has been developed in ARENA simulation package. The processing time is taken as random variable with normal distribution. Design decision considers the manufacturing flexibility (sequencing and routing flexibility) and the number of AGVs used. System load condition and system configuration is taken as planning decision where as the control decision covers the part dispatching rules, sequencing rules and AGV velocity. The simulation model of SFMS has been verified with the help of facilities available in ARENA package. After performing full factorial experimentation we applied the Taguchi methods of design of experiment and the results were analyzed by using analysis of variance (ANOVA). The data normality and constant variance assumption were also checked with a normal probability plot of residuals and residuals versus fitted value plot respectively.

The research shows that for a given set of system configuration, a given level of flexibilities and number of AGVs offers maximum benefit. The load condition as well as sequencing rule has an impact on all the performance measures. It is found that the performance is improved with the increase of routing flexibility in all of the combinations but this increase of the performance is more from RF0 to RF1. It is also observed that the number of AGVs and AGV velocity has a significant impact on the SFMS. More importantly from the results we find that the combination of two flexibilities provides a significant improvement in all the performance measures of the SFMS.

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Abbreviations

AGV	Automated guided vehicle
AGVs	Automated guided vehicles
ANFIS	Adaptive neuro-fuzzy inference system
ANOVA	Analysis of variance
AS/RS	Automated storage and retrieval system
BC	Buffer capacity
DIB	Dedicated input buffer
DIS	Decision-Information Synchronization
FCFS	First come first serve
FMS	Flexible manufacturing system
GRAI	Graph and results and architects interconnected
HPT	Highest processing time
LBMUPT	Load Balanced on Machine and Unbalanced Processing Time
LCFS	Last come first serve
LFB	Load fully balanced
LIB/LOB	local input/output buffer
LUB	Load fully unbalanced
LUMBPT	Load Unbalanced on Machine and Balanced Processing Time
MBPT	Maximum balance processing time
MINQ	Minimum number of parts in queue
MQMWT	Minimum queue with minimum waiting time

MST	Makespan time
PAC	Production Activity Control
RF	Routing flexibility
RU	Resource utilization
SC	System capacity
SF	Sequencing flexibility
SFMS	Stochastic flexible manufacturing system
SL	System load
SLC	System load condition
SPT	Shortest processing time
SR	Sequencing rules
WIP	Work in process

Chapter 1

Introduction

1.0 Background

In the present global market, manufacturers are facing highly competitive, complex and dynamic industrial environment. The manufacturing performance is not only driven by the price of the product but other factors such as flexibility, quality, and delivery also have equal importance. Thus there is a need to provide customized product to customers with better quality. In such a dynamic and competitive scenario, it is necessary to fulfill the requirements of the customer. Apart from other competitive factors, the challenge involves lead-time reduction while dealing with a variety of products. To cater a variety, the systems require flexibility in various forms. So, flexibility in manufacturing system is the most sought after property to take in account the stochastic condition in the manufacturing system. Hence, the manufacturers require production technology that can operate efficiently under stochastic manufacturing system environment. Manufacturing system with the provision of manufacturing flexibility is known as Flexible Manufacturing System (FMS). It helps in producing variety of parts keeping in mind the customer's need. It is observed that FMS is one of the widely used area of exploitation being tapped by researchers for stochastic manufacturing system environment. Hence an attempt is being made in this research work towards phased development in FMS under stochastic environment.

Judicious focus on flexibility and its exploitation through effective design, planning and control decisions operating under various information support environments offer several challenges. This thesis addresses an important theme, with a specific focus on enhancing the research on improving the time-based and other performance of manufacturing systems through flexibility, under various real life operating factors at shop floor. Therefore, to become more responsive to the stochastic manufacturing, an environment manufacturers must consider performance measures like makespan time, work-in-process and resource utilization. The flexible manufacturing system with different types of flexibility helps to manage effectively different flows in the system such as material, automated guided vehicles, information, decisions etc.

1.1 Motivation

Our initial motivation is based on different decisions related to design, planning and control of flexible manufacturing system operating under stochastic environment. Since the parts are operated at various operational conditions, the flexible manufacturing system due to its inherent flexibility will take care of the variation in operational conditions to give the desired output (Browne et al. 1984). Thus, FMS is the emerging requirement along with its components such as computer numerical control machines, automated guided vehicles, automated storage and retrieval system etc. which play a more proactive role. Despite number of works done in the area of flexibility in manufacturing system still more work is to be done in this domain. This includes different decisions, related to design, planning and control of various parameters in FMS. The proposed models will help the management to take judicious decisions regarding the choice of different parameters for effectively operating FMS under stochastic environments. From the research point of view, the task mentioned above becomes very complex when we model FMS under stochastic environment.

1.2 Flexible Manufacturing System (FMS)

Browne et al. (1984), defines, the FMS is a fully computerized integrated, manufacturing system that can produce mid-variety and mid-volume of parts. This small batch production system can produce a large product mix and also a wide range of manufacturing resources. The workload in the system needs to control properly in order to reduce makespan, work-in-process and achieve maximum utilization of different resources in the system. Similarly, Sabuncuoglu and Lahmar, (2003) have defined that FMS is a manufacturing system consisting of computer numerical control machines, automated material handling system and computer-controlled network. The right type and level of manufacturing flexibility is needed to cope up with uncertain product demand, product variety and uneven distribution of shop load. FMS further helps to reduce manufacturing lead time, improve product quality, increase productivity and decrease manufacturing cost that helps the user to remain competitive and survive in the global market. These benefits are possible because FMS is an interactive system consisting of flexibilities with material handling system. Material handling system in manufacturing industries has drastically changed with the use of automated guided vehicle (AGV). The efficient use of AGVs with FMS would help to achieve routing flexibility. The need for automated material handling system evolved in response to the problems faced by traditional manufacturing system. However, it is essential to integrate AGVs in manufacturing system before the design of a FMS.

1.2.1 Flexibility

Flexibility is a multi-dimensional concept and it can either be reactive or proactive in nature (Hyun and Ahn 1992). It reacts to the environmental internal and external uncertainty. The proactive natures of flexibility help to redefine market uncertainties or influence that what are the expectations of customers from the industry (Gerwin, 1993).

1.2.2 Manufacturing Flexibility

Different types of manufacturing flexibility are reported in the literature. Browne et al. (1984), defined that the system has two basic types of flexibilities i.e. machine flexibility and routing flexibility. Based on these two basic types of flexibilities, some other types of flexibilities may be derived such as product flexibility, process flexibility, operation flexibility, volume flexibility, expansion flexibility and production flexibility. Similarly Koste and Malhotra (1999) also defines some more flexibilities like machine flexibility, routing flexibility, volume flexibility, material handling flexibility, operation flexibility, labor flexibility, mix flexibility, new product flexibility, expansion flexibility and modification flexibility. They further divide these manufacturing flexibilities on the basis of levels in the organization at which they are applied. The levels in the organization could be at the plant level, functional level, shop floor level and individual resource level. Flexibility is achieved by better integration of information available in the system. The available information helps to take appropriate design, planning and control decisions in realizing flexibility in the manufacturing system.

1.3 Automated Guided Vehicles (AGVs)

An automated guided vehicle performs the function of material handling. They perform functions like movement of finished or unfinished parts, protection and control of materials during the manufacturing and distribution and also include their utilization and disposal. Today, computerized control machines are available which considerably reduce the machining time and set-up time. Therefore, the production planning decisions have moved from fast production of parts to efficiency of their transportation between different stations. AGVs are the appropriate choices where different materials are transported from various load and unload points. AGVs are therefore appropriate for automating material handling in batch production industries as well as for mixed modal production system. One of the major areas of application of AGVs is in FMS. The use of the flexibility of AGVs helps to efficiently control work flow in the manufacturing system. A centralized buffer in the form of automated storage and retrieval system can be used to prevent blocking in the system.

1.4 Shop floor control of FMS under stochastic environment

The shop floor control is responsible for converting the production requirements into specific instructions for the specific equipment and interacting with the equipment to implement the instruction (Wysk and Smith 1995). The aim of the shop floor control is to identify the sequence of different decisions in a way to accomplish the job in a best possible manner. Shop floor control traditionally consists of multiple operation steps that need to be completed in order to complete the product. The control decisions related to shop floor will monitor the material flows within the system. In particular, it encompasses sequencing and dispatching of parts in the system. The researchers in the area of FMS have always assumed a real-time availability of information for decision markers, especially at the operation levels. The real-time access to information is considered certainly beneficial under stochastic environment. Thus we develop the concept of Stochastic Flexible Manufacturing System (SFMS) to emphasize the use of design, planning and control decisions within the domain of FMS. The evolving manufacturing system requires manufacturing flexibility to take care of uncertainty within and outside the system. Implementation of manufacturing flexibility requires huge investment hence the system designer/practitioners needs to apply only the required types and levels of flexibility. Hence there is need to take required design, planning and control decisions to harness different types and levels of manufacturing flexibility on their requirement.

1.4.1 Design decisions of FMS

The present manufacturing systems are purely based on the choice of alternatives decisions. The design decisions normally considered in FMS include manufacturing flexibility, buffer size and number of AGVs. The better the decision more will be the improvement in the performance of the system. Stecke (1995), considered overall flexibility of a manufacturing system as one of the design decision for FMS. Rachamadugu et al. (1993) noted that the sequencing flexibility is a design decision for the manufacturing system. Shafiq et al. (2010) proposed a framework for studying the effect of many parameters along with buffer capacity, on the performance of FMS.

1.4.2 Planning decisions of FMS

A suitable planning decision is necessary for enhancing the flexibility, resource utilization and efficiency of a flexible manufacturing system. There are various objectives of planning decisions considered by the researchers. Planning decisions includes system load conditions, system configurations and batch size. The problems related to distribution of work between the machines are known to be the load balancing problem.

Machine processing time balancing and unbalancing the machine load was considered by the Stecke (1983). Kumar et al. (2006) considered that the machine loading decision is an important decision in manufacturing system. There are number of system configurations considered by various researchers. Sabuncuoglu and Lahmar, (2003) studied the performance of the manufacturing system consisting of six multi-purpose machines. The system comprises a loading and unloading station that also includes a central buffer storage area of predetermined capacity. In addition of central buffer there was provision of input and output buffers of finite capacity at each machine. As it is known that an FMS is capable for producing variety of part types in small to medium sized batches in contrast to the high rate of production in traditional assembly lines. The need to decide the batch size is primarily based on buffer capacity with balancing and maximizing flexibility of the manufacturing system.

1.4.3 Control decisions of FMS

Flexible manufacturing system has the ability to manufacture mid-variety and mid-volume of parts. Job dispatching and sequencing problems in flexible manufacturing systems are dependent on the efficient and effective allocation of limited resources to improve the performance of FMS. But the determination of operational sequence of the parts is an important decision in controlling the FMS. Stecke (1985) described about the choice of parts to be machined using control of sequence method. Byrne and Chutima (1997) considered the operational control decisions of a flexible manufacturing system with flexible alternative operation sequences and flexible alternative machines. Sequencing and dispatching of the parts are considered as the control decisions in the system. In this research work velocity of AGVs is also considered under control decisions of AGVs.

1.5 An overview of Stochastic Flexible Manufacturing System

The struggle for variety of products with high quality, low cost and shorter response time always predominate in every competitive industry. Therefore, manufacturing system becomes very complex and stochastic with a larger set of uncertainties. It presents many difficulties encountered by different decisions to be taken on the shop floor. These decisions relate to design, planning and controlling of the system. The decision making situation is further complicated when manufacturing facility is enhanced by adding more resources in the system. In order to help the managers/practitioners to take judicious decisions regarding implementation of the FMS system in stochastic environment there is need of right type and levels of manufacturing flexibility. It is important to assess the performance of stochastic flexible manufacturing system under the influence of various design, planning and control decisions. Also we need to know about manufacturing system parameters, which may contribute more to improve the performance of the system. This research work investigated the effect of several factors such as manufacturing flexibility (sequencing and routing flexibility), AGVs (number and velocity), buffer size (system capacity) under stochastic part inter-arrival and processing time, makespan time, work-in-process and average resource utilization performance of the system. Hence keeping in view the evolving manufacturing environment, our area of study is stochastic flexible manufacturing system (SFMS) with a decision focus similar to FMS.

At the shop floor level the frequencies of various decisions over a given time frame are much higher. These may have significant effect on the performance of the SFMS. Wadhwa and Browne (1990) stated that there is a need to control the flow of entities such as parts, information and resources in the manufacturing system. Hence the system under consideration i.e. SFMS will process the products that are physically flowing entities, the resources are the machines and AGVs, the information is the status of jobs and resources. In the stochastic manufacturing environment, control decisions incorporate the uncertainties of the system. These decisions are usually taken through the application of sequencing and dispatching rules. The sequencing rules assign priority to various jobs that are waiting at the queue of the machine. The job with highest priority is performed first as compared to lesser priority. Depending on the level of scheduling, sequencing decision is made on the shop floor. In order to fully address different design, planning and control decisions at the shop floor level should be considered in unison. This research presents a model, which integrate AGVs in SFMS domain with different types of manufacturing flexibilities. Hence studying the affect of design, planning and control decisions on the performance is a step towards the phased development of SFMS.

1.6 Organization of Thesis

The organization of the thesis is as follows. It consists of 10 chapters.

In Chapter 1, the background and motivation related to the use of FMS under stochastic manufacturing environment are provided. This chapter highlighted the relevance of different design, planning and control decisions in prevailing stochastic manufacturing environment.

In Chapter 2, the foundation of the thesis topic, a study of stochastic flexible manufacturing system (SFMS) in the domain of FMS is a set through the literature review. This chapter presents the ideas and views of the previous researchers in the areas of shop floor control of FMS. Three distinct decisions of shop floor control in FMS are reviewed as design, planning and control decisions. Beside these aforementioned decisions, reviews on computer simulation, specifically discrete event simulation are also presented. The shortcomings of the previous researches are identified.

In Chapter 3, the research methodology adopted to develop this thesis as well as the research motivations and objectives are discussed.

In Chapter 4, the conceptual framework of stochastic flexible manufacturing system (SFMS) in the domain of FMS is presented. Then the demonstration models of SFMS were built in ARENA simulation package. Multiple type and levels of design, planning and control decisions are incorporated in the models. The brief description of the proposed SFMS system is also explained.

In Chapter 5, various results focusing on the effect of sequencing flexibility on the makespan, work-in-process and resource utilization performance of the system are described. The experiments are performed under four system load conditions i.e., Load Fully Balanced (LFB); Load Balanced on Machine and Unbalanced Processing Time (LBMUPT); Load Unbalanced on Machine and Balanced Processing Time (LUMBPT) and Load Fully Unbalanced (LUB). The sequencing rules considered is FCFS, SPT, HPT and LCFS. The experiments are conducted with system having dedicated input buffer (DIB) with variable capacity. This chapter deals to find the answers to the following question: How do various levels of sequencing flexibility impact on the system performance under the influence of various system load conditions? Is the makespan, work-in-process and resource utilization performance of SFMS significantly superior at various level of sequencing flexibility? Does the performance become comparable at various level of sequencing flexibility? What will be the nature of performance variation on increasing the level of sequencing flexibility? Is sequencing flexibility beneficial with increase in the quantities of parts in the system? What are the suitable quantities at which maximum benefit may be obtained from the system? What is the nature of performance variation as the number of parts is increased in the system?

Data focusing on the effect of routing flexibility on the makespan, work-in-process and resource utilization performance of the system are presented in chapter 6. The experiments were performed under four system load conditions i.e., Load Fully Balanced (LFB); Load Balanced on Machine and Unbalanced Processing Time (LBMUPT); Load Unbalanced on Machine and Balanced Processing Time (LUMBPT) and Load Fully Unbalanced (LUB). FCFS, SPT, HPT and LCFS are considered as sequencing rules. The experiments are conducted with system having dedicated input buffer (DIB) with variable capacity. In this chapter following question were addressed: How do various levels of routing flexibility impact the system performance under the influence of various system load conditions? Is the makespan, work-in-process and resource utilization performance of SFMS significantly superior at various level of routing flexibility? Does the performance become comparable at various level of routing flexibility? What will be the nature of performance variation on increasing the level of routing flexibility? Is routing flexibility beneficial with increase in quantities of parts in the system? What is the suitable quantity of parts at which maximum benefit is obtained from the system? What is the nature of performance variation as the quantity of parts is increased in the system?

In Chapter 7, various results focusing on the effect of automated guided vehicles on the makespan, work-in-process and resource utilization performance of the system are described. The experiments are performed under four system load conditions i.e., Load Fully Balanced (LFB); Load Balanced on Machine and Unbalanced Processing Time (LBMUPT); Load Unbalanced on Machine and Balanced Processing Time (LUMBPT) and Load Fully Unbalanced (LUB). The same sequencing rules were again considered (FCFS, SPT, HPT and LCFS). The experiments are conducted with system having dedicated input buffer (DIB) with variable capacity. This chapter deals to find the solutions to the following problems: What is the effect of number of AGVs on makespan, work-in-process and resource utilization performance measure of the system? What is the effect of AGV's velocity on makespan, work-in-process and resource utilization performance measure of the system?

In Chapter 8, the data on the effect of both sequencing flexibility and routing flexibility on the makespan, work-in-process and resource utilization performance of the system is explained in detail. The experiments were performed under four system load conditions i.e., Load Fully Balanced (LFB); Load Balanced on Machine and Unbalanced Processing Time (LBMUPT); Load Unbalanced on Machine and Balanced Processing Time (LUMBPT) and Load Fully Unbalanced (LUB). The same sequencing rules are repeated as earlier. The experiments are conducted with system having dedicated input buffer (DIB) with variable capacity. In this chapter we have tried to reveal following issue: How do combination of sequencing and routing flexibility impact the system performance under the influence of different load conditions and sequencing rules? Which performance measures give better results at different system load conditions? Is it advisable for the practitioners to operate the system with sequencing flexibility or routing flexibility or combination of both the flexibility types?

In Chapter 9, the analysis under Taguchi's experimental framework was performed to study the multiple flexibility types and other decision factors. Their relative effects on the various performance measures of SFMS are also presented. This chapter will help in finding the best combination of various flexibility and other factors with an objective to maximize the system performance.

In Chapter 10, we summarized the findings of all the above results. Manufacturing flexibility is demonstrated to be a useful concept to improve makespan, work-in-process and resource utilization performance of stochastic flexible manufacturing system. This chapter highlights some useful insights in the direction of effective benefits of the design, planning and control decisions that is being implemented. The salient contributions are discussed. Moreover, directions for future research are also suggested.

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Literature Review

2.1 Introduction

Implementation of FMS or any sub-system of FMS, in a stochastic environment is one of the expensive and complex problems of an organization. In this section a literature review was carried out to explore the potential research efforts and directions related to our work. The review is being carried out on flexibility, manufacturing flexibility, flexible manufacturing system, AGVs, AS/RS, buffers, shop floor control, performance measures, simulations, system configuration, etc. While reviewing the papers in the concerned area, efforts were made to highlight not only the researcher's viewpoint but also to find out how it relates to our work. The literature review will help us to obtain important research issues and objectives for our research work.

2.2 Flexibility

Flexibility was first introduced by George Stigler in 1939 as reported by Carlsson in 1989. But the concept of flexibility is still not understood by the practitioners and researchers. A flexible system is system, which accommodates the ability to cope with customers' preference changes. There are several types of flexibility mentioned in literature. Sethi and Sethi (1990) recognize flexibility as a multi-dimensional notion within the manufacturing domain. Flexibility may be reactive or proactive in nature. The reactive nature of flexibility considers the environmental uncertainties, i.e. internal uncertainties as well as external uncertainties, faced by an organization, whereas proactive nature of flexibility allows an organization to redefine market uncertainties and customers' expectations from a particular industry (Gerwin, 1993). Beach et al., (2000) stated that manufacturers in countries like Japan and Korea give credit to the application of flexibility for their success. Although many researches have been cited that the flexibility as a key competitive capability. Koste et al., (2004) has compared a subset of firms in respect to their flexibility types, and observed that the firms make trade-offs both within and across flexibility context. They further observed that adding the more flexibility features in a flexible manufacturing system increases the complexity as well as cost. Implementation of different flexibilities in an uncertain manufacturing environment is an expensive affair as well as difficult to understand and quantify (Chauhan et al. 2007). Therefore, Ali and Wadhwa (2010) suggested that a judicious decision is required for designing an FMS to select the right level of flexibility. Chauhan and Singh (2011) further stated that flexibility is the ability of a system to accommodate the changes in the system and react according to the situation in a complex and uncertain environment. Joseph and Sridharan (2012) studied the effect of sequencing flexibility, routing flexibility and part sequencing rules of a typical flexible manufacturing system on different performance measures i.e. flow time and tardiness of parts. They revealed that the system performance can be improved by incorporating either routing flexibility or sequencing flexibility or both. Recently Singh and Singh (2013) also advocated that flexibility in manufacturing management plays a vital role in today's most changing and turbulent environment of the market.

2.3 Manufacturing Flexibility

There are number of different manufacturing flexibility types reported in literature. Cheng et al. (1997) defined three types of flexibilities that are diversity flexibility that handles the variety of parts, response flexibility that deal with the rate of change and volume flexibility that is related to the magnitude of change. Sethi and Sethi (1990) proposed eleven types of flexibilities adding three more that is material handling, program and market flexibility to this list of Brown et al. (1984). Thomke (1997) proposes and defines design flexibility as the incremental cost and the time of modifying a design. Koste and Malhotra (1999) presents definition often types of flexibility namely; machine flexibility, routing flexibility, operation flexibility, material handling flexibility, volume flexibility, mix flexibility, labor flexibility, expansion flexibility, new product flexibility, and modification flexibility. Beach et al. (2000) reveals that the manufacturing flexibility is a strategic objective, further they discussed the types of flexibilities, the nature of flexibility, and its measurements. Braglia and Petroni (2000) presents an empirical study to classify different types of flexibilities that are machine flexibility, routing flexibility, process flexibility, product flexibility, volume flexibility, expansion flexibility, and layout flexibility. From the above review we observe that there are numerous types of manufacturing flexibilities that are addressed in the literature. Koste et al. (2004) addressed the use of related manufacturing flexibility measure and develop a better understanding of the manufacturing flexibility by providing scope verses achievability relationship among the various flexibility factors. Baykasoglu (2009) presents a novel approach that is based on digraph/matrix representation for quantifying flexibility. The proposed flexibility model is able to enlighten the capability, capacity, probability and their change in computing the flexibility. By far the taxonomy of manufacturing flexibility as proposed by Brown et al. (1984) describe the flexibility in most comprehensive manner that is as follow

- Machine flexibility: the changes required to produce a given set of part types is ease.
- Process flexibility: the ability to produce different parts types, using different materials, in different ways.
- Routing flexibility: the ability of handling breakdowns of the machines in the system without bring to halt in producing the given set of part types.
- Product flexibility: the ability to changeover the system to produce a new set of parts economically and efficiently.
- Production flexibility: the universe of part types that the FMS can produce.
- Volume flexibility: the ability of a system by which the system operate profitably at different part volumes.
- Expansion flexibility: the capability of a manufacturing system for further expansion as and when needed, easily and modularly
- Operation flexibility: the ability to interchange the sequence of different operations for each part type.

Table 2.1: Flexibility Types studied by different researchers

Manufacturing Flexibility type	**Citations**
Expansion/diversity flexibility	Brown et al. (1984), Koste and Malhotra (1999), Braglia and Petroni (2000), Kara and Kayis (2004).
Machine flexibility	Browne et al. (1984), Chandra (1992), Koste and Malhotra (1999), Braglia and Petroni (2000), Wadhwa and Rao (2000), Sethi and Sethi (1990), Barad et al. (2003), Zhang et al. 2003), Karuppan& Ganster, (2004), Wahab (2005), Wahab et al., (2008), Baykasoglu (2009).
Response flexibility	Cheng et al. (1997), Wahab (2005).
Volume flexibility	Cheng et al. (1997), Zhang et al. (2003), Wahab (2005).
Sequencing flexibility	Chandra (1992), Beach (2000), Wadhwa (2005), Li and McMahon (2007), Wang et al. (2012), Joseph and Sridharan (2012).

Routing flexibility	Brown et al. (1984), Chandra (1992), Byrne and Chutima (1997), Koste and Malhotra (1999), Braglia and Petroni (2000), De et al. (2003), Zhang et al. (2003), Karuppan and Ganster (2004), Chan et al. (2006), Baykasoglu (2009), Shafiq et al. (2010), Joseph and Sridharan (2012).
Management flexibility	Cheng et al. (1997), Singh and Singh (2013).
Design flexibility	Thomke (1997).
Material handling	Sethi and Sethi (1990), Koste and Malhotra (1999), Zhang et al. (2003).
Program flexibility	Sethi and Sethi (1990).
Market flexibility	Sethi and Sethi (1990), Kara and Kayis (2004).
Labor flexibility	Koste and Malhotra (1999), Zhang et al. (2003), Karuppan and Ganster, (2004), Kara and Kayis (2004).
Operation flexibility	Brown et al. (1984) Koste and Malhotra (1999), Karuppan and Ganster (2004).
Volume flexibility	Brown et al. (1984), Koste and Malhotra (1999), Braglia and Petroni (2000), Zhang et al. (2003), Baykasoglu (2009).
Mix flexibility	Koste and Malhotra (1999), Zhang et al. (2003), Karuppan and Ganster (2004), Wahab (2005), Baykasoglu (2009).
New product flexibility	Koste and Malhotra (1999)
Process flexibility	Brown et al. (1984) Braglia and Petroni (2000), Kara and Kayis (2004), Karuppan and Ganster (2004), Li and McMahon (2007), Mak and Shen (2009).
Product flexibility	Brown et al. (1984), Braglia and Petroni (2000), Zhang et al. (2003), Karuppan and Ganster, (2004), Wahab (2005).
Layout flexibility	Braglia and Petroni (2000).
Modification flexibility	Koste and Malhotra (1999).

In the field of manufacturing there is an important factor to select an appropriate type and level of flexibility for effective and efficient run of the system. However, a comprehensive understanding of the manufacturing flexibilities is required. An extensive review of the different types of manufacturing flexibilities is given that were considered by the number of researchers. Here it is observed that almost all the researchers suggested that flexibility is a philosophy of performing job with many alternatives. Therefore sequencing flexibility and routing flexibility are considered here for further exploration in a stochastic manufacturing environment.

2.4 Flexible Manufacturing System

Flexible Manufacturing System (FMS) is defined as a fully automated manufacturing system (Stecke et al. 1984 and Sethi and Sethi 1990). Stecke and Solberg (1981) have proposed the approach to solve the problem of production-planning in FMS. She had build up a general framework in which the whole problem is divided into several hierarchical structured sub-problems like selection of part-type, grouping of machines, production ratio and allocation of resources, machine loading and scheduling of parts. According to Wadhwa and Browne (1990), flexibility provides alternative decision for discrete events. On the basis of manufacturing flexibility present in the system, a decision point provides opportunity for controlling the way in which the system should evolve. Control decisions can be with the help of sequencing and dispatching rules. A new perspective for viewing a flexible manufacturing system as a whole control system is proposed by Jia and Li (1991). They develop a real-time feedback control model for the FMS. Sarma et al. (2002) develops a modeling framework that addresses the machine-loading problem of FMS. Chan et al. (2006) developed a system to identify productive and counterproductive performance of an FMS at different flexibility levels by considering physical and operating characteristics of the FMS. And also express the necessity of modeling clearly, the physical and operating characteristics of a system with flexibility, and a simulation study was presented for the given FMS. Venkata and Manukid (2008) proposed a methodology based on a combinatorial mathematics-based decision-making method for the evaluation of alternative flexible manufacturing systems.

The methodology was developed to judge the relative merits of different flexible manufacturing systems for the industrial application. Several stochastic modeling methods have been applied to FMS reliability and performance. Different aspects of the manufacturing flexibility have been explored by the researchers. Therefore a judicious decision is needed for implementing the right level of flexibility under different operating conditions, because it incurs cost in the system (Ali and Wadhwa, 2010). Singholi et al. (2010) suggested some methods for the improvement in the performance of an FMS. They developed mathematical model to estimate the possible performance parameters like maximum production rate, makespan time and overall utilization. Shafiq et al. (2010) proposed a framework for evaluating the performance of a flexible manufacturing system in respect to makespan time, machine utilization, cost and queue. Wang et al. (2012) focuses on the continuous quality improvement in flexible manufacturing systems. For this they established a Markov chain model to assess the product quality in flexible manufacturing systems. Safitra et al. (2014) studied flexible manufacturing systems in stochastic environment and stated that the successful implementation of the flexible system will increase the capital utilization and competitiveness.

2.5 Automated Guided Vehicles (AGVs)

The concept of Automated Guided Vehicle System (AGVS) was first applied in 1974 on a large scale manufacturing at a Volvo plant in Kalmar, Sweden. This emerges as an important part of material handling system in an FMS. Because the AGV system provides the flexibility and adaptability, which is requires for a material handling system in an FMS environment. AGVs are now used in almost all types of industries. The most of the applications of AGVs are technically feasible, but the procurement and implementation of it is based on economic considerations.

Much research has been done to analyze the performance and increase the efficiency of the AGVs. Performance of the AGVs is measured in many ways by different researchers. Taghaboni and Tanchoco (1995) used a simulation technique to study the effectiveness of a new dynamic approach for the routing of AGVs. Klien and Kim (1996) selected some of the performance measures like queue length and load waiting time in each department, vehicle travel time, and job completion time for the comparison of single and multi-attribute dispatching rules. The superiority of the multi-attribute dispatching rules is demonstrated for these measures. There are numerous factors that affect the efficiency of an AGV system including the routing and scheduling of the vehicles in the system. Qiu and Hsu (2001) analyzed the efficiency of the system in terms of the distance traversed and the time requirement for AGVs to complete the task. Koo and Jang (2002) stated that the performance of dispatching rules varies with the travel time in an AGV based material handling FMS. Ho and Hsieh (2004) proposed a design methodology for Automated Guided Vehicle (AGV) systems with multiple-loads. They design a methodology that can minimize the flow distance, inter-loop flow and achieve the workload-balance between vehicles of different loops. Farahani et al. (2007) considered a single loop, with at least one shared edge with each cell, the direction of flow and the location of pickup/drop-off stations on the loop, and uses a Tabu search method for minimizing the total travel distance on the loop. Sedehi and Farahani (2009) developed an integrated algorithm for designing system facilities as well as material handling system in an FMS. They focused on the single-loop AGV system. The developed algorithm can also be resolved the issues of block layout, single-loop AGV flow path and loading/unloading stations. Rezapour et al. (2011) developed an algorithm that simultaneously determines the routing of AGVs and machines layout. Sharma et al. (2013) said that the FMS is an intensive and complex task of capital-investment. They also discussed various crucial aspects that are required for the implementation of flexible manufacturing system. Even then, the control of AGVs in FMS is a challenging problem. Eduardo et al. (2014) developed hybrid control architecture for the group of AGVs in flexible manufacturing system that based on the Petri net model by using the industrial standard ISA-95. They adopted a systematic approach which uses the concept of discrete-event system in the context of manufacturing. Although the automated material handling systems is more flexible and capable than non-computer controlled material handling systems, but the implementation and control of such systems have some serious challenges at the operational level.

2.6 Automated Storage and Retrieval System (AS/RS)

Automated Storage and Retrieval Systems (AS/RS) is an automated material handling system that is controlled by computers and facilitate all the operations which are required for material transportation i.e. unloading goods from carrier, to the loading of finished parts for shipment. Although, there is need to explore the subject of AS/RS and finds out the performance of the system under different type of demands. Much of the work is carried out by many researchers. Some of the recent work is being discussed here.

Yavuz and Myeonsig (2005) concerned about the throughput performance of an AS/RS with stochastic demand. In fact, the simulation is a primary tool for the analysis of an AS/RS with random storage and retrieval requests. Assuming a particular dwell point strategy for the storage and retrieval system, they derived analytical results in closed-form to compute the performance of an AS/RS under stochastic demand and determine whether it fulfils throughput or not. Hur and Nam (2006) considers single or dual commands in an automated storage and retrieval system with two waiting points and one server point. It is assumed that the storage and retrieval commands in the system arrives according to Poisson processes and that the service times of single and dual commands are differently distributed. Sari et al. (2007) studied the performance of flow-rack automated storage and retrieval system. They reported that flow-rack systems are beneficial to reduce inventory levels, while maintaining product variety and response to the customers' need in a timely manner. Fukunari and Malmborg (2008) proposed a cycle time based computationally efficient model for conceptualizing autonomous vehicle storage and retrieval systems and compare the performance of proposed model with crane-based AS/RS. The model works on random storage and queuing model approximations. It covers the realistic sized sample problems. Shunji and Mituhiko (2008) discussed the routing problem for unit-load AS/RS with different input and output points. The shared storage policy is considered in this study. In this study they try to find an optimal travel route for storage and retrieval machine to process specified request so that the total travel time is reduced, where the input and output points are possibly different. Gonzalo and Carlos (2008) considered the blocking of the manufacturing system and introduce a Petri net-based approach for scheduling of the jobs to avoid the system blocking. The modeling of the job routings is carried out with the Petri net formalism due to their capability of representing dynamic, concurrent discrete-event dynamic systems. They conceder makespan time is the optimization criterion.

2.7 Shop Floor Control in FMS

The manufacturers are always keen to evaluate the FMS performance prior to establishing costly investment in the shop floor. There are various difficulties come across in the shop floor control such as taking design, planning, and control decisions of the FMS. Smith and Joshi (1994) stated that the shop floor control is responsible for planning, scheduling and controlling the events on the shop floor. Roy et al. (2001) proposed multi agent platform to take care of dynamic shop floor control problems in real-time. Researchers have proposed and considered the concurrent control capabilities, particularly at the shop floor level in an FMS (Ali and Wadhwa 2010).

The present work focuses on the selection of design, planning and control decisions of the proposed SFMS. Manufacturing flexibility, buffer size and number of AGVs are considered as design decisions, system load condition and system configuration are taken as planning decisions and dispatching rules, sequencing rules and AGV velocity are considered as control decisions for SFMS.

2.7.1 Design Decisions in FMS

The decisions related to selection of manufacturing flexibility, buffer size and number of AGVs are considered as design decisions by many authors. Singholi et al. (2010) stated that the designing of the flexible environment is a fundamental decision in the flexible manufacturing system to survive and grow in the market. Chan and Chan (2004) considered that routing and sequencing flexibility are the important factors of an

FMS. The underlying principle of routing flexibility is to deals with short term conflicts, such as breakdowns and changes in requirements by enabling material handling, flexible transporting network and on-line control. Routing decisions involve selecting the routes that should be followed by each part in the production mix to maximize use of resources utilization. Browne et al. (1984), states that routing flexibility is exhibited when machines break down. Pankaj and Mihkel (1991) incorporates the reliability of machines to study routing flexibility. Wadhwa and Bhagwat (1998) explained that the makespan performance of an FMS deteriorates due to increase in delaying decision at higher levels of routing flexibility. Zhao and Wu (2001) used genetic algorithm for the scheduling of FMS with multiple routes. Barad and Sapir (2003) stated that routing flexibility is the ability of a system for processing parts through different routes, or by using alternate machines. But it is noted that the setup time is a significant part of the lead time. Therefore routing flexibility has a considerable effect on the manufacturing lead time Wahab (2005). There are various manufacturing flexibilities mentioned in the literature but Chen et al. (2006) stated that all the manufacturing-related flexibilities are derived by the routing flexibility in the FMS. Wadhwa et al. (2008) studied the impact of routing flexibility on the system performance under various planning and control strategies in flexible manufacturing system. Ali and Wadhwa (2010) defined that the increase in the routing flexibility level does not imply that there is an improvement in the system performance. Mehdi et al. (2013) presented the ways to explore the meta-heuristics such as ant colony optimization, genetic algorithms, simulated annealing and tabu search are adopted for reducing the congestion of parts in the system.

Sequencing flexibility refers to the chance of interchanging operation order in which the required manufacturing is performed. Rachamadugu et al. (1993) noted that the sequencing flexibility is a design decision for the manufacturing system. Benjaafar and Ramakrishnan (1996) considered several issues related to the sequencing flexibility in a manufacturing system such as modeling, measurement and performance evaluation of the FMS. Chan (2001) found that there is only a minor difference in the system performance with fixed sequencing of operations and flexible sequencing system. As stated by Choi and Lee (2004) sequencing of job is an important stage in designing of an FMS. Such as different parts requires different operations at different machines and with different production priorities. A conceptual study and simulation experimentation is planned for understanding sequencing flexibility by Wadhwa et al. (2005) that assist reduction in manufacturing lead-time. Agnetis et al. (2009) discussed the problems related to the assigning and sequencing of the jobs on the machines so that the expected total reward is maximized. Sridharan and Joseph (2011) revealed that the deterioration in system's performance can be reduced considerably by incorporating either sequencing flexibility or routing flexibility or both of the flexibilities. However, the benefits of any one of these two flexibilities reduce as we move to the higher levels of flexibility. Job sequencing has an impact on the product quality (Wang et al. 2012). Interaction among sequencing flexibility, routing flexibility and part scheduling in an FMS were investigated by (Safitra et al. 2014). Moreover, his work revealed that the benefits of each flexibility diminishes the performance of the system at higher levels of flexibility. In view of the above studies the routing flexibility and sequencing flexibility are having an important place in designing of an FMS. Therefore we consider the impact of these two important manufacturing flexibilities i.e. sequencing flexibility and routing flexibility on the performance of SFMS.

Buffer size is defined as the maximum number of parts that can be stored in the in-process inventory. Buffers can be used as a safety stocks because they minimizes the risk due to a sudden breakdown. If breakdowns happen, production can be continued by pulling parts from buffers. The output performance of the system is determined by that of the limited resource. Any interruption in the constraint's output rate means a decline in the system output and, consequently, has a significant effect on the revenues. In view of this, buffers should be kept large. But in contrast, the buffer uses exclusive floor space therefore it is need to kept it low. We expect that the buffer size have a positive impact on the output, since larger it offers more protection against breakdowns and assure to maintain the continuity of the process flow. Vidyatrhi and Tiwari (2001) considers job ordering/sequence before loading and evaluating the characteristics of the jobs such as batch size and processing time. As reported by (Sabuncuoglu and Kizilisik 2003) the system performance is to some extent improved when the capacity of buffer is kept too large (i.e. unlimited buffer capacity). Chan and Chan (2004) investigated the effects of local buffer sizes, changing the ratio of part mix and machine failure in the context of FMS and they suggested that the infinity buffer size is not a good choice for an FMS. Haung et al. (2008) used a hybrid algorithm to study more complex FMS with alternative routing, limited buffer size, and dual resource. Ruiz et al. (2009) studied a painting shop having two machine stations with an automated articulated arm for material handling and dedicated buffer for each machine. Among many constraints in the design of FMS local input/output buffer (LIB/LOB) size is one of the important technical constraint of a manufacturing system that effect the operative efficiency of the FMS (Shirazi et al. 2010). Shafiq et al. (2010) proposed a framework for studying the effect of many parameters along with buffer capacity, on the performance of FMS. Reddy and Rao (2011) evaluated the performance of the flexible manufacturing system with dedicated input and output buffers by using a discrete event simulation package 'Automod'. Kulkarni and Bhatwadekar (2015) studied an integrated dynamic scheduling system by considering the factors that influences the performance of FMS such as buffer sizes, material handling system, etc. and tested these factors for different sizes of dynamic scheduling problems. The above studies have been concerned with the use of buffer space with the machines in order to improve the overall improvement of the system. The present work considers the impact of varying buffer capacity in SFMS with stochastic environment.

Jaikumar and Solomon (1990) studied the performance of AGV based manufacturing system. Their prime objective was to exploit the utilization of machines and reduce the total travel time and fleet size. Klien and Kim (1996) compared single and multi-attribute dispatching rules for some of the selected performance measures like vehicle travel time, job completion time, queue length and load waiting time in each department. Scheduling of AGVs means to send off a set of AGV to pick up the jobs from a centralized loading station and dispatch them to different workstations according to their priority. Routing of AGVs involves is to find out a suitable route, e.g., shortest time path, shortest distance path, or minimal energy path for every vehicle from its origin point to its destination point based on the current situation. Ho and Hsieh (2004) proposed that smaller fleet size also means fewer occurrences of traffic congestions. The vehicles may travel forward or backward therefore there is need to avoid the collision of vehicles on the guide path. Lacomme et al. (2005) addressed the scheduling problem in automated manufacturing environments. They studied the sequencing and vehicle dispatching problems. A benchmark test is performed to investigate the system performances. They stated that the makespan time depends on the job input sequencing the vehicle dispatching and machine. Correa et al. (2007) considered 6 AGVs traveled at a constant velocity of 0.5m/s in his study. The design and implementation of AGVs in an FMS require answers to a number of problems, like routing algorithms, controller devices and guide path design of the AGVs. The problem of scheduling of vehicles and machines in flexible manufacturing systems is simultaneous addressed by Deroussi et al. (2008). Now a day's conflict free and shortest time, multiple automated guided vehicle system is the prime requirement of an FMS (Srivastava et al. 2008). Ho and Liu (2009) evaluate the performance of single-load and multi-load AGVs and reveals that multiple-load AGVs have numerous advantages over the single-load AGVs. They observed that the fleet size may be reduced if we use multiple-load vehicles in place of single-load vehicles. Subbaiah et al. (2009) used sheep flock heredity algorithm to determine the optimal sequences of AGVs and machines and predict the entire set of flow requirements for a given machine schedule and vehicle assignment are prepared accordingly. AGV systems are considered as one of the most appropriate means for material handling system of contemporary flexibly manufacturing environment (Lengerke et al. 2010). Kamble and Kadam (2012) considered an FMS with number of single-load AGVs that travels at a speed of 40m/min. for their study so as to minimize the makespan time of the FMS.

A priority analysis of the variety of incoming jobs into the system efficiently were studied by Bramhane et al. (2014) and develops an adaptive neuro-fuzzy inference system (ANFIS) to calculate the priority of incoming jobs based on slack remaining operations parameter. They also developed a system to generate best priority of incoming jobs. With the incorporation of the above discussed flexibilities and some of the control factors in any of the manufacturing system that becomes a flexible manufacturing system. Ahmad et al. (2014) explained the experimental design issues of the FMS under stochastic environment. They investigated the effect of different input factors by considering the part inter-arival time and processing time is stochastic. In this research work operation time and inter arrival time of the parts are considered as the probability distribution. Therefore the operation time for each of the operation is generated from the given mean and standard deviation to develop the stochasticity in the manufacturing system. Eduardo et al. (2014) developed hybrid control architecture for the group of AGVs in flexible manufacturing system based on the Petri net model by using the industrial standard ISA-95. They adopted a systematic approach by using the concepts of discrete-event systems in context of engineering manufacturing, and also classify the applications of continuous motion control law of automated guided vehicles in flexible manufacturing systems. All though the automated material handling system is more capable and flexible than non-computer controlled material handling systems, but along with all merits it possesses very challenging and serious operational control problems. Rashmi and Bansal (2014) have made an attempt to find the optimum solution by using Ant Colony Optimization algorithm. This results increase in AGV utilization and hence the overall efficiency of the system will increased. Here in this research work number and types of AGV used in the system are taken as a design decision in the shop floor control. In view of the above background we selected bi-directional single load AGVs. Moreover, its performance was evaluated on the bases of variable speed.

2.7.2 Planning decisions in FMS

Planning decisions include system load conditions, system configurations and batch size. The problems related to distribution of work on the machines are known as load balancing problem. Decisions related to machine loading receive their inputs from the prior decisions for example resource layout, part types, and batch size that generate inputs to the dynamic operations planning and control. Stecke and Solberg (1981) studied the part sequencing and machine loading problem by using simulation technique. Hwang (1986) stated that the part selection and machine loading are considerably crucial planning decisions for enhancing the performance of a production system. Sarma et al. (2002) develops a modeling framework that addresses the machine-loading problem of FMSs. The machine loading problem involve job sequence determination, system throughput and system unbalance at the same time the model also satisfies a number of technical constraints like machine time, limited tools slots etc. Srinivas et al., 2004) studied five loading policies and sixteen dispatching rules. In view of these rules they stated that system performance of FMS is highly dependent on loading and controling strategies. Kumar et al. (2006) considered that the machine loading decisions are acting as an important relation between strategic and operational level in a manufacturing system. Biswas (2007) addressed the problem of machine load balancing in very detailed manner. He was noted that throughput and system unbalance can be improved if overloading of machines is permitted. But, it is necessary to justify the overloading of machine economically before allowing overloading of machine. Ali and Wadhwa (2010) observed that system load condition has a large impact on the performance of the system when the number of pallets in the system has the smallest value. Kumar et al. (2012) stated that the machine loading problem is considered as one of the most important production planning decisions because the operational effectiveness of FMS is mostly depends on it. Singh et al. (2014) considered that better balancing machine workloads is an important property of the decision domains and it provide the potential for improving the performance of an FMS.

The above review of literature is concerned about the machine load balancing in order to improve the performance of FMS by optimum utilization of machines. Here in this research work the evaluation is at various load conditions and some important parameters on the bases of makespan, work-in-process and resource utilization. There are number of system configurations considered by various researchers. Sabuncuoglu and Lahmar, (2003) have considered a system comprises of six multi-purpose machines and a central buffer area of finite capacity. And each machine also has an input and output buffer of limited capacity. Chan, (2004) has studied the impact of operational flexibility and dispatching rules on the performance of FMS. He considered FMS consisting of twelve machines having input buffers of finite capacity. There was common buffer of infinite capacity to take care of blocking of the system. Mohammed and Wadhwa (2005) considered six machines to study the performance of flexible manufacturing system in computer integrated manufacturing system context. Ruiz et al. (2009) in their study considered a manufacturing system consisting of different type of resources. They developed a performance algorithm minimize the number of resources needed by the system.

Biswas (2007) and Kumar et al. (2012) address the loading problem in a random FMS of three set of system configurations. These three system configurations are on the bases of number of machine (i.e. 4, 5, and 6 numbers of machines). It is considered in the study that all the jobs and machines are initially available for work and transportation time of the job between machines was negligible. Mehdi et al. (2013) considered seven machines and a load and an unloading area with six different part types for the study. Singh et al. (2014) investigate the behaviour of the system in order to explore the impact of routing flexibility. The four flexible machines, three part types of finite size and six different operations have been considered for his study. Keeping in view of the above literature in respect to the system configuration different researchers uses different number of machines. In this research work we formulated an FMS of six fully flexible machines with a variable capacity dedicated machine buffers, a loading and unloading station and controlled part entry in the system of variable batch size.

An FMS at the same time is capable of producing a variety of jobs in small to medium size batches and at a high rate, in comparison to the conventional assembly lines which are designed for high volume and low-variety of jobs. The need to decide the batch size is primarily that of buffer capacity constraints, with balancing and maximizing flexibility of the manufacturing system. Huang et al. (2008) developed an algorithm that may be applied to a set of randomly generated more complex FMS with limited buffer sizes, i.e. size of each buffer was limited to 1-3, as well as the lot size of each job was 1-3, too. Nanvala and Awari (2011) noted that batch size is one of the important characteristic that contributes in the determination job ordering/job sequence before loading in the system. Mallikarjuna et al. (2013) made an attempt to consider the machine arrangements in a most favorable sequence with flexible batch size as constraints in an FMS. Kulkarni and Bhatwadekar (2015) considered three types of jobs in different batch sizes that vary from one to ten jobs per batch. In view of the above literature we considered batch size from six to twenty four parts in a step of six parts and part mix is at the ratio of 1:1.

2.7.3 Control decisions in FMS

Job dispatching and sequencing problems in flexible manufacturing systems are mainly dependent on the effective allocation of the available resources. The system has been strongly affected by the effective choice of sequencing and dispatching rules. These rules are considered as the control decisions of a flexible manufacturing system by Caprihan et al. (2013). Klien and Kim (1996) compared single and multi-attribute dispatching rules for some selected performance measures i.e. queue length, vehicle travel time, job completion time and load waiting time in each department. Chan et al. (2002) proposed an intelligent fuzzy decision support system for real-time part dispatching in a flexible manufacturing system, with the possibility of alternative routs for all jobs to improve the performance of system by considering various performance measures. As revealed by the number of researchers Caprihan et al. (2004), Kumar et al. (2005), Caprihan et al. (2006), Caprihan et al. (2007), Chan et al. (2008) the FMS is designed for quick response for varying demands and static control approaches, that will be based on the proper information system and optimal control decisions (i.e. dispatching and sequencing decisions). All they stated that any conventional control decision causes great deterioration in systems performance. Wadhwa et al. (2008) considered sequencing and dispatching rules the control decisions at the shop floor level of an FMS. They selected SPT and maximum balance processing time (MBPT) are the sequencing rule whereas the minimum in queue (MINQ) and minimum queue with minimum waiting time (MQMWT) are the dispatching rules. For studying all the above, the make-span time is considered as the performance measure. However, this paper presents a real time simulation and the effects of routing flexibility with the different sets of sequencing and dispatching rules. Ali and Wadhwa (2010) used the combination of sequencing rules (i.e. SPT, MBPT, FCFS and LCFS) and dispatching rule (i.e. MINQ) rule as control strategies at four levels of routing flexibilities. Nanvala (2011) proposed a fuzzy-based methodology that shows a better performance compared to the conventional dispatching rules. Caprihan et al. (2013) investigate the impact of information delays in flexible manufacturing system in many ways. They noted that the performance of the system declines by using the obsolete information when making dispatching/sequencing decisions. They also noted that as the magnitude of review period decreases, an FMS comes closer to a real-time operating condition.

The review of literature on control decisions recommended that a number of dispatching and sequencing rules have been proposed by the researchers for controlling an FMS under various environments. Here in this research work MINQ is selected as a dispatching rule in combination of four sequencing rules (i.e. FCFS, SPT, HPT and LCFS) to evaluate the performance of an FMS in respect to makespan, work-in-process and average resource utilization.

2.8 Performance Measures

Performance measures are used to assess accountability and make decisions. It is difficult to decide whether the selected performance measures are having any relevance with objective of the study. Performance information of the system provides data to achieve the goals and objectives of the system, but it does not provide the information needed to evaluate whether the goals and objectives of the organization are the most appropriate one and ones that most evidently reflect the values of the goals. In order to measure anything we need to understand its dimension and the metrics or measures along these dimensions (Wadhwa and Rao, 2002). There are a large variety of performance measures that are usually used in manufacturing simulation studies, like makespan, WIP, equipment utilization, throughput, and the time jobs spend in queue. In an expensive system like FMS, high equipment utilization is of prime motive of the researchers. Performance criteria like make-span and average resource utilization were used by many researchers for evaluating performance of FMS (Azimi et al. 2010; Singholi et al., 2010; Kumar and Sridharan, 2011). A successful implementation of flexibilities in any of the manufacturing system leads the decrease in production cost, lead time, inventory, tooling, direct labor content, floor space, Work-in-Process and assembly (Saygin et al., 2001). In the present research work we will consider makespan, work in process, average resource utilization as performance measures to study the performance of the SFMS under stochastic environment.

2.8.1 Makespan

The total time requires for completing all of the jobs is said as makespan time. To improve the system performance there is need to minimize the makespan time. For minimizing it a proper sequencing of jobs are required. Li and McMahon (2007) studied the impact of operation sequencing flexibility, scheduling flexibility and processing flexibility on various performance measures of manufacturing system like make-span, the balanced machine utilization, manufacturing cost and job tardiness. Wadhwa et al. (2008) studies the makespan performance of FMS under planning and control strategies with different routing flexibility. Ali and Wadhwa (2010) considered make-span as the performance measure to study an FMS with variation in routing flexibility. Sharma et al. (2013) presented a comprehensive review of various issues involved in flexible manufacturing system. They revealed that make-span is one of the key measures to evaluate the performance of an FMS. Al-Kahtani et al. (2014) concluded that the makespan decrease where as machine utilization and production cost increase with the increase of routing flexibility level. Kazim et al. (2014) developed codes in C++ for getting optimum sequence of operation to minimize the makespan time and reduce the machine idle time and minimize the utilization of machines. The benefit of minimizing the makespan is that parts spend less time in the shop. This decreases the cost of the carrying an inventory of unfinished parts on the shop floor. Also there is a decrease in the inventory of finished parts that are waiting for other parts to be processed. As noted by the researchers that makespan is a critical performance measure for a manufacturing system. So that in this present work makespan is considered as performance measure for the SFMS.

2.8.2 Work-in-process

The implementation of above mentioned modules in an FMS are required to judge on the bases of performance measures many of the researchers evaluate the system with the makespan as mentioned in the above discussion. There are very few researchers they uses work-in-process as a performance measure in the recent years. Reduction in WIP and manufacturing lead times is the most positive response that would made with regard to the performance improvement of an FMS. Vieira et al. (2003) noted that the issues like WIP reduction, total cost minimization, job profitability, etc. are more important for managers then time base performance measures. Through simulation Mehdi et al. (2013) showed that production rate, machine and material handling utilization rate for an over-loaded manufacturing system, the real-time rescheduling outperforms without rescheduling, but it has a counter impact on WIP. Singh et al. (2014) recorded statistical data such as WIP levels and cycle time as an output report in the simulation model developed in ARENA simulation software.

2.8.3 Resource Utilization

Resource utilization may be defined as the actual percentage of machine working time. It may be increases as and when the job comes in the system it is to be possessed by machine. When the system is lightly loaded, the faster machine tends to process all of their jobs. As the system becomes heavily loaded, less efficient machines steadily take on more work, until a saturation point reached. Al-Titinchi and Al-Aubidy (2004) presented an interactive hierarchical model based on colored petri net for general flexible manufacturing system and evaluated the performance of the system in respect to machine utilization, average flow time and maximum flow time. They noted that there is an insignificant effect of the sequencing priority on these performance measures. Singholi et al. (2010) presented a case study of a firm and suggested some methods for the improvement in the performance of a flexible manufacturing system. They explored make span time, overall machine utilization and maximum production rate as the performance measures. Burnwal and Deb (2013) presented a cuckoo search (CS) - based approach for scheduling optimization of an FMS by reducing manufacturing delay penalty and increase in the machine utilization. It has been implemented by using computer software Matlab and the results have been verified with genetic algorithm and particle swarm optimization. The results shows that the CS-based approach has been found batter performance in compare to the existing algorithms such as genetic algorithm. Kazim et al. (2014) developed codes in C++ for getting optimum sequence of operation to minimize the makespan time and reduce the machine idle time and minimize the machine utilization.

2.9 Simulation

A system may be defined as a collection of entities usually machines, materials, people that interact towards the achievement of some logical goal (Law and Kelton 1991). The above definition of system helps us to develop the methodology and model parameters for SFMS. Simulation is defined as the execution of a virtual process which corresponds to the operations of real environment under preset conditions. Mahmoodi et al. (1990) used computer simulation to test scheduling rule under various levels of shop load. Similarly Mohammed and Wadhwa (2005) evaluated the performance evaluation of partial FMS with the help of simulation. Wadhwa et al. (2008) studied the performance of FMS under planning and control strategies with the help of simulation. They developed a simulation model of a manufacturing system consisting of six machine and six parts. Singholi et al. (2010) judged the performance of proposed FMS by developing a simulation model in ARENA simulation software after the calculation of desired operational parameters has been done. They explained that ARENA is SIMAN based simulation software which uses various inbuilt modules to model any situation in a graphical user interface. Chen and Jiang (2011) stated the simulation is a well-proven method for designing as well as for analyzing a flexible manufacturing system. Taktak et al. (2012) stated that many real world problems in optimization are very complex and mathematically interacted so that simulation is an appropriate tool for analysis and performance evaluation. Singh et al. (2014) developed simulation model for understanding the behavior of the system and to explore the impact of routing flexibility in ARENA simulation software. They also noted that the ARENA simulation modeling software is a powerful and flexible tool that allows researchers to create an animated simulation model that represents the virtual system accurately. Kumbhaj and Patil (2014) in his research focus on the loading problem of production management with variable production ratios. They developed a simulation model to investigate an FMS performance while minimizing the workload unbalance.

There are two broad classifications of simulation. These are continuous-state simulation and discrete-event simulation. The system where the notion of state is continuous are known as continuous-state simulation while discrete-event simulation is applicable where the state of the system changes at discrete interval of time, with a finite number of changes occurred in any infinite interval of time. Since we will focus on end-to-end system rather than continuous system therefore we will consider the discrete-event simulation.

Discrete event simulation is considered as powerful tool to facilitate the understanding and managing a complex manufacturing system. Zaied (2008) discussed how a combined process or discrete-event simulation modeling can be used to schedule the process orders. He presented results of a comparative simulation study on flexible routing and prefixed routing of jobs in an FMS which was subjected due to unexpected machine breakdowns. Ali and Wadhwa (2010) applied Taguchi's method for identifying the vital parameters and discrete event simulation was used to study the various factors contributing for improving the performance of an FSIM. Chen and Jiang (2011) stated that FMS is a typical discrete event system. Although it is difficult to assess the efficiency of an FMS by conventional methods because of its complexity and randomness therefore simulation is a well-proven technique for designing and analyzing an FMS. Taktak et al. (2012) relates the use of computer simulation through the development of computer-assisted applications (e.g. ARENA simulation software) in assessing a manufacturing system. The main aim of the research is to assist a new user in applying the process of discrete event simulation, and to simplify the setting of possible configurations. Caprihan et al. (2013) used simulation experiment for empirical estimation of the impact of information delays. They also noted that experimental design of the simulation study is a unique feature of Taguchi's robust experimental design that is used to select the factor arrays for experiments. Kulkarni and Bhatwadekar (2015) studied a system comprising of total 11 number of machines of five types, three types of jobs are processed in different batch sizes and four job loading and unloading stations. They applied discrete event methodology to evaluate the bases of makespan of the job and number of tardy jobs.

In simulation of any system the objective could be simply to reduce the cost of production by enhancing the system performance. With the introduction of computers the simulation has become the computer based simulation. There are two distinct types of simulation widely used i.e. deterministic simulation and stochastic simulation. Stochastic simulation is in nature with probabilistic translation rules. This type of simulation gains the popularity among the researchers because it is close to the realistic environment.

Rupe and Kuo (2001) evaluated effectiveness of an FMS through stochastic process modeling of the failure and repair of the FMS components. They applied the Markov model with the assumptions that all operations are having random durations and are exponentially distributed. Vieira et al. (2003) discusses the affect of rescheduling on the performance of the manufacturing system and also stated that stochastic static rescheduling environment is a special case of rescheduling of parts. Sabuncuoglu and Kizilisik (2003) was generated the processing time from a truncated normal distribution using mean equal to the estimated processing time and coefficient of variation is 0.4 from the actual processing times of the manufacturing. Much of the work has been conducted on deterministic environment of manufacturing system whereas the real manufacturing systems are of stochastic nature. Therefore stochastic variables and constraints may not be handled by conventional approaches (Varadharajan and Rajendran 2005). Gu et al. (2009) stated that the analysis of stochastic flexible job shop is more complex than conventional job shop because of stochastic as well as flexible nature of the system. Due to the diversity of performance criteria, choosing a good system design becomes a crucial decision Mahdavi et al. (2010) stated that discrete-event stochastic simulation optimization algorithm is able to evaluate multiple stochastic performance criteria. Ozcan et al. (2011) stated that in the real life application the jobs may have varying execution times that may define as a probability distribution. They considered stochastic times for studying the sequencing and mixed-model U-line balancing problems. They also performed a computational study for deterministic as well as stochastic nature of the problem to evaluate the efficacy of the proposed algorithm. Savsar and Aldaihani (2012) analyzed the effects of various parameters, including corrective maintenance capacity and repair crew allocation policy on the performance of a manufacturing system having two machines and a robot. They particularly considered a stochastic environment to compare productivity of a manufacturing system under different corrective maintenance policies.

2.10 Design of Experiment

Experimentation helps us in understanding the nature of any system. In experimentation process the required data is gathered by systematic variation of important factors that help to describe the underlying facts quantitatively. The aim for designing the experiments is to get the maximum information about the system with the minimum number of experiments. In this system of experiment design factors may be identified by looking at the quantities that affect the performance of the system. This facilitate designer to find out the individual as well as the interactive effects of the factors simultaneously that may affect the output performance of the system. The number of experiments to perform depends on the number of factors and their levels if the number of factors and their levels are less then full factorial design of experiment is possible. In case of full factorial experiment design method we have to follow the following process that we vary one factor at a time, perform experiments for all levels of all factors, all interactions are captured, therefore large number of experiments are required to perform (e.g. 4 factors with 4 levels each, 256 experiments are required) to find the interactive effect of among every factor at all level. Yang and Chen (2001) established a systematic procedure of using Taguchi method of experiment design to find the important parameter design in process control of individual milling machines. Ghani et al. (2004) used Taguchi optimization technique to optimize cutting parameters while machining hardened steel (e.g. feed rate, cutting speed and depth of cut). The robust design of flank milling parameters (i.e. cutting forces, surface roughness and material removal rate) of an aluminum alloy casting for injection moulds was presented by (Kopac and Krajnik 2007). They used Taguchi's method of experiment design with the combination of orthogonal array to determine the optimal combination of milling parameters for multiple process responses. Moshat et al. (2010) has been used Principal Component Analysis (PCA) based Taguchi method to solve a multi-objective optimization problem of CNC end milling process parameters. Yuvaraj et al. (2012) stated that the Taguchi's experiment design is an important tool for vigorous design of any system. It presents a simple and systematic approach to optimize the design of any system for getting best performance (i.e. quality and cost). Francis et al. (2013) was explored Taguchi's method for designing the experiment using, an L_{27} orthogonal array. They selected and the three process parameter, depth of cut, feed and spindle speeds that varied to analyze the results obtained in order to find the optimal levels of the parameters for minimum surface roughness and maximum material removal rate. In this research work we selected 4 parameters with 4 levels for each parameter. After full factorial experimentation we applied the Taguchi's method of experimental design with L_{16} orthogonal array to find the best interactive factors.

2.11 Statistical analysis

Statistical analysis is a fundamental tool for all experimental studies. It is very useful to get approximate solutions in case when the actual process is very complex in its true form. Statistics may be defined as the collection, analysis, organization and presentation of the useful information. It deals with all aspects of data including the planning of data collection in terms of design of experiment. Rao and Padmanabhan (2012) used a statistical technique i.e. analysis of variance (ANOVA) to specify the impact of process parameters on values of rate of metal removal. Francis et al. (2013) obtained results via experimental runs for metal removal rate and surface roughness. They were used ANOVA for finding out the significant parameters, at confidence level of 95%. Raju et al. (2014) used analysis of variance (ANOVA) to manipulate and validate the experimental results in order to determine each factor effect versus the response variable-strength of the stereolithography prototypes.

2.12 Conclusions

In this chapter, an attempt has been made to focus on the previous research effort and direction related to our research area. The literature review on FMS suggests real-time decision-making has been mainly emphasized at the shop floor control level or operational levels. The literature also indicates that in the case of FMS it is implicitly assumed that a real time control facilitates scheduling decisions to exploit the advantages of manufacturing flexibility.

In practice, the planning, design, and control decision may have an impact on SFMS performance in FMS context. Some research efforts have reported on the impact of some of these decisions on the makespan, work-in-process and resource utilization performance of FMS at an operational level. However, there are many research gaps that exist to enrich this domain. This thesis attempts to contribute to this domain with a focus on the planning, design and control decisions within a discrete part manufacturing system. In this chapter, we have identified some interesting research issues of SFMS in the domain of FMS. These are highlighted in Chapter 3.

Chapter 3

Research Methodology and Objectives

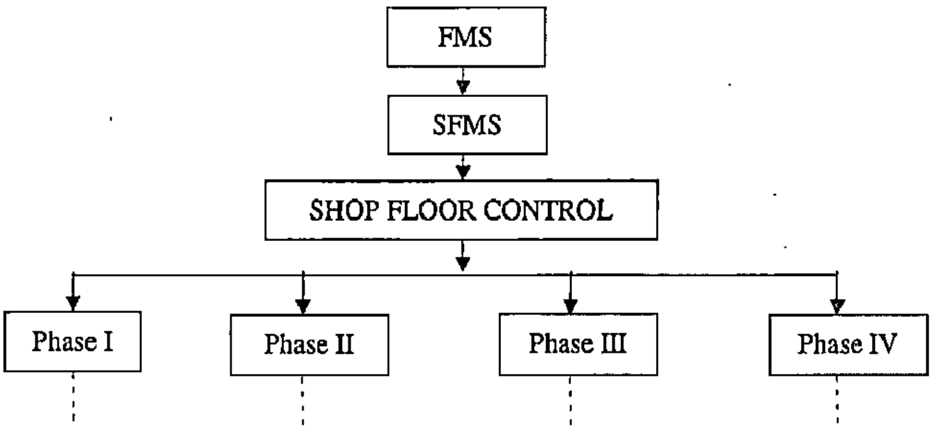
3.1 Introduction

The modern manufacturing system is becoming very stochastic and fiercely competitive. The challenges involve evaluating the stochastic flexible manufacturing system with multi criteria performance measures. Literature indicates that the evolving competitive environment is shifting towards time-based competition. Customers want the products to be delivered as soon as possible. Hence, there is need for greater focus on makespan, work-in-process and resource utilization performance of the system. Our particular interest is on the interactions between various types of design, planning, design and control decisions. We are motivated to research in this domain as it offers significant potential benefits through a closer understanding of the role of flexibility in FMS operating under stochastic environment.

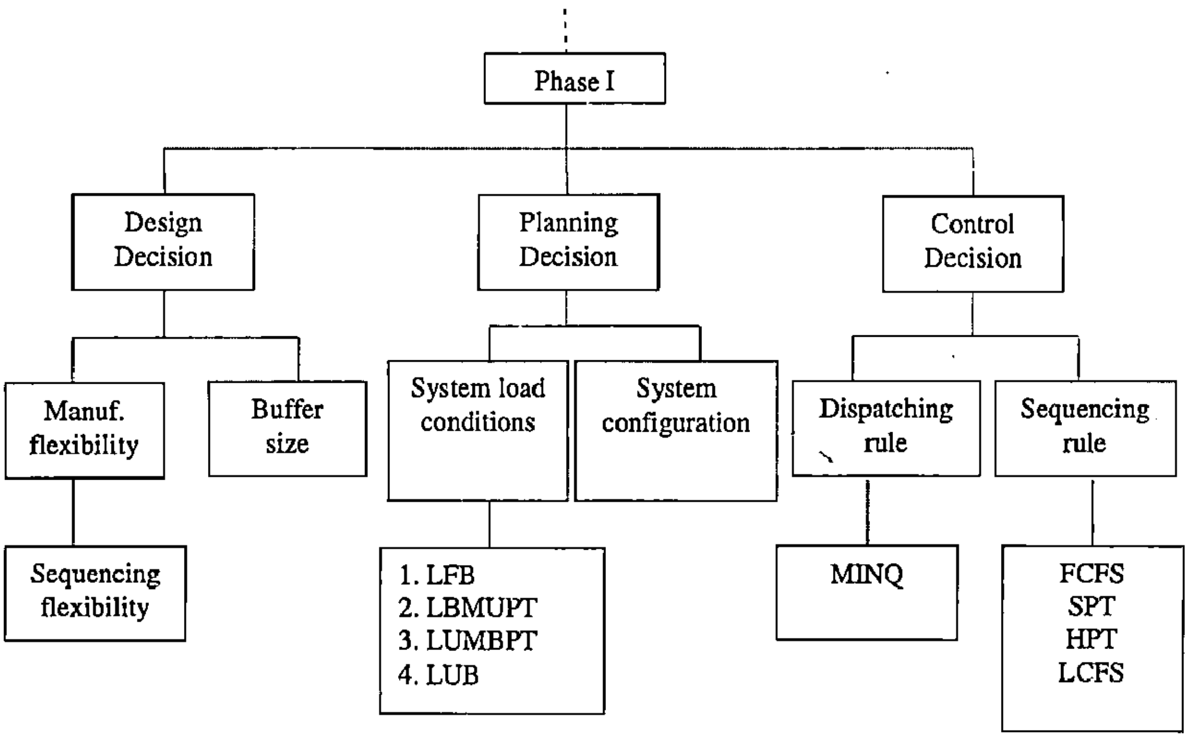
This research focuses on the design, planning and control decisions needed for phased development of FMS under stochastic environment. Design decisions include manufacturing flexibility, buffer size and number of AGVs. Planning decisions include system load conditions, system configuration and batch size. Control decisions include sequencing and dispatching of parts in the system.

FMS may be considered, as platforms where various design, planning, and control decisions can be judiciously implemented to obtain maximum benefits. In this direction Stochastic Flexible Manufacturing System (SFMS) has been suggested to be a building block in phase development of FMS. The core theme of our research effort is the study of design, planning, design and control decisions and their impact on the makespan, work-in-process and resource utilization performance of SFMS. This work will help the practitioners/managers take judicious decisions and invest in key factors that will improve the system performance. There is need to develop a conceptual framework and a simulation model as a platform to research the impact of design, planning and control decisions in SFMS. The models would act as demonstration platform for practitioners/managers on the usefulness of SFMS systems.

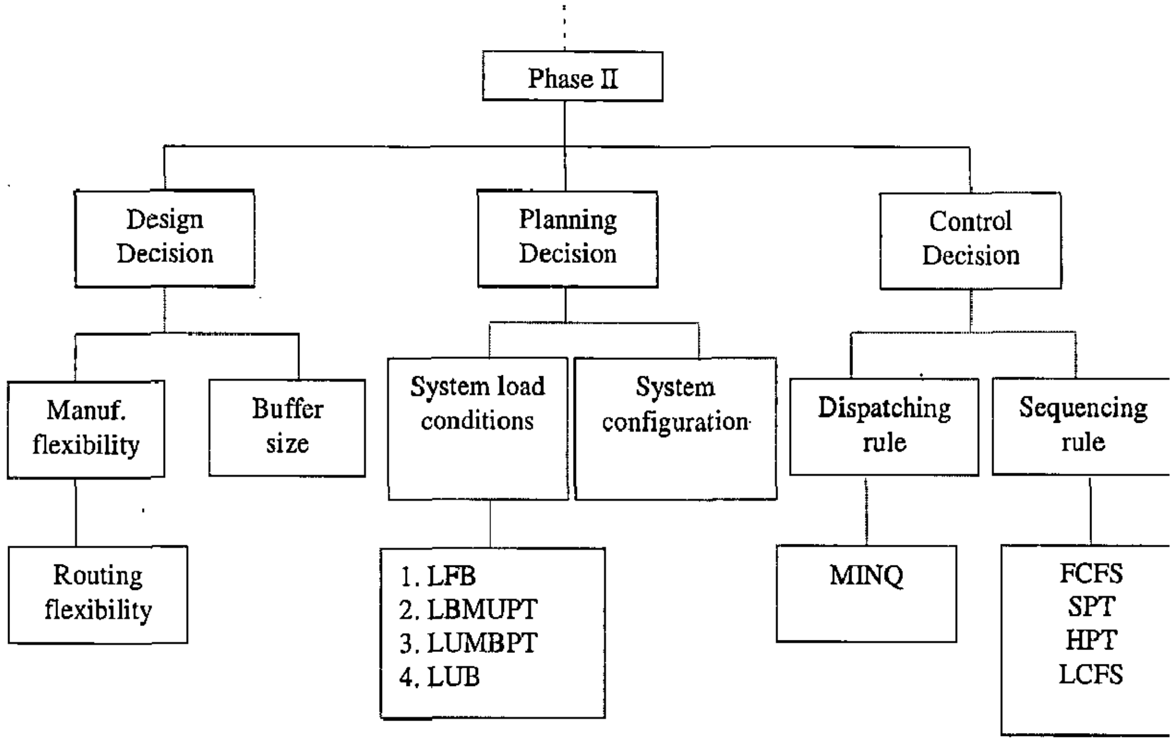
With the above background, Figure 3.1 summarizes the research context and the main theme pursued by this thesis. As shown in this figure, the overall theme is to study the performance of SFMS in evolving FMS environment. There are number of options available to improve the performance of FMS under stochastic environment. This thesis focuses on the effective implementation of design, planning and control decisions to enhance the makespan, work-in-process and resource utilization based performance of the system. The thesis area has been contributed by various researchers in the past (Rachamadugu et al. 1993, Wadhwa and Bhagwat1998, Zubair et al. 2001 Framinan et al. 2003, Sharif et al. 2004, Mohammed and Wadhwa 2005, Li and Yuan 2006, Chan et al. 2007, Ali and Wadhwa 2010, etc). The main objective of this thesis was to enrich the domain of SFMS operating with various design, planning and control decisions. All these decisions are implemented in phased manner. In all SFMS is developed under four phases as shown in Figure 3.1 (a). In the first phase design decisions considered is sequencing flexibility with different buffer size, planning decisions include different system load conditions and system configurations and control decisions include dispatching and sequencing rules (see Figure 3.1 (b)). Similarly in the second phase we consider the impact of routing flexibility on system performance keeping all other factors same as that of phase I (see figure 3.1 (c)). In the third phase we consider the impact of number of AGVs and its velocities on system performance keeping all other factors same as that of phase I (see figure 3.1 (d)). In the fourth phase we are motivated to know the effect the combined effect of sequencing and routing flexibility on the system performance keeping all other factors remaining the same (see figure 3.1 (e)).



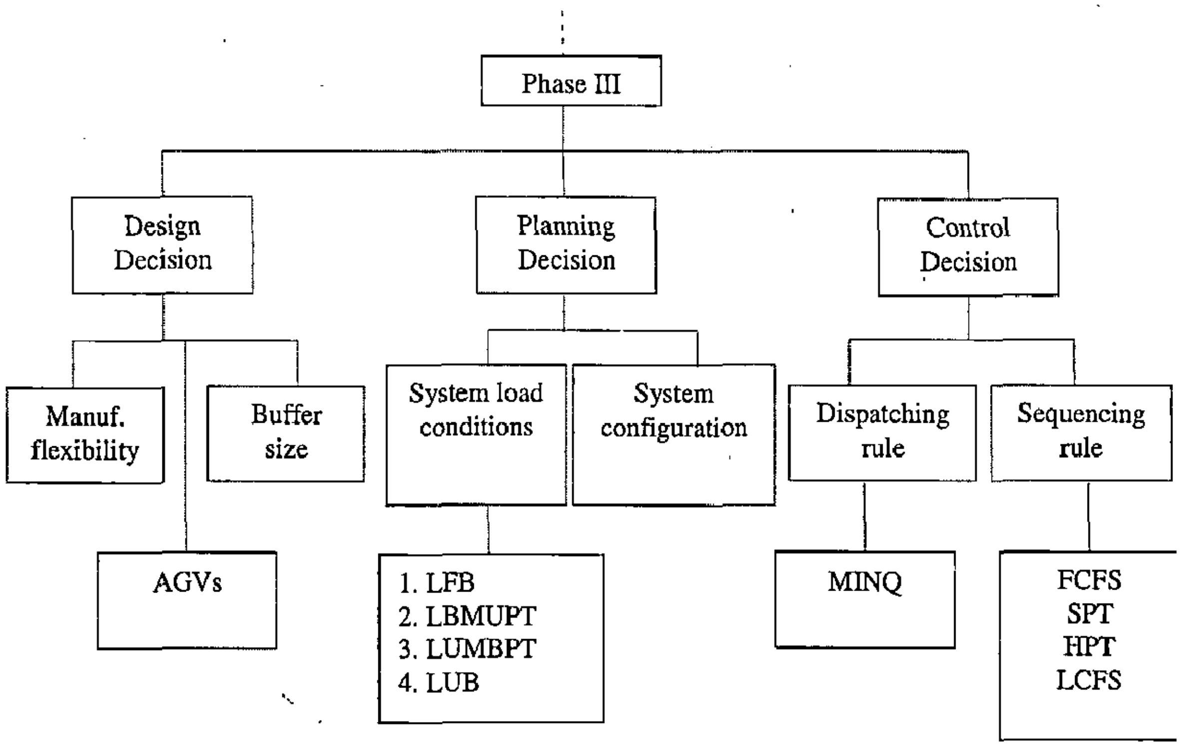
(a)



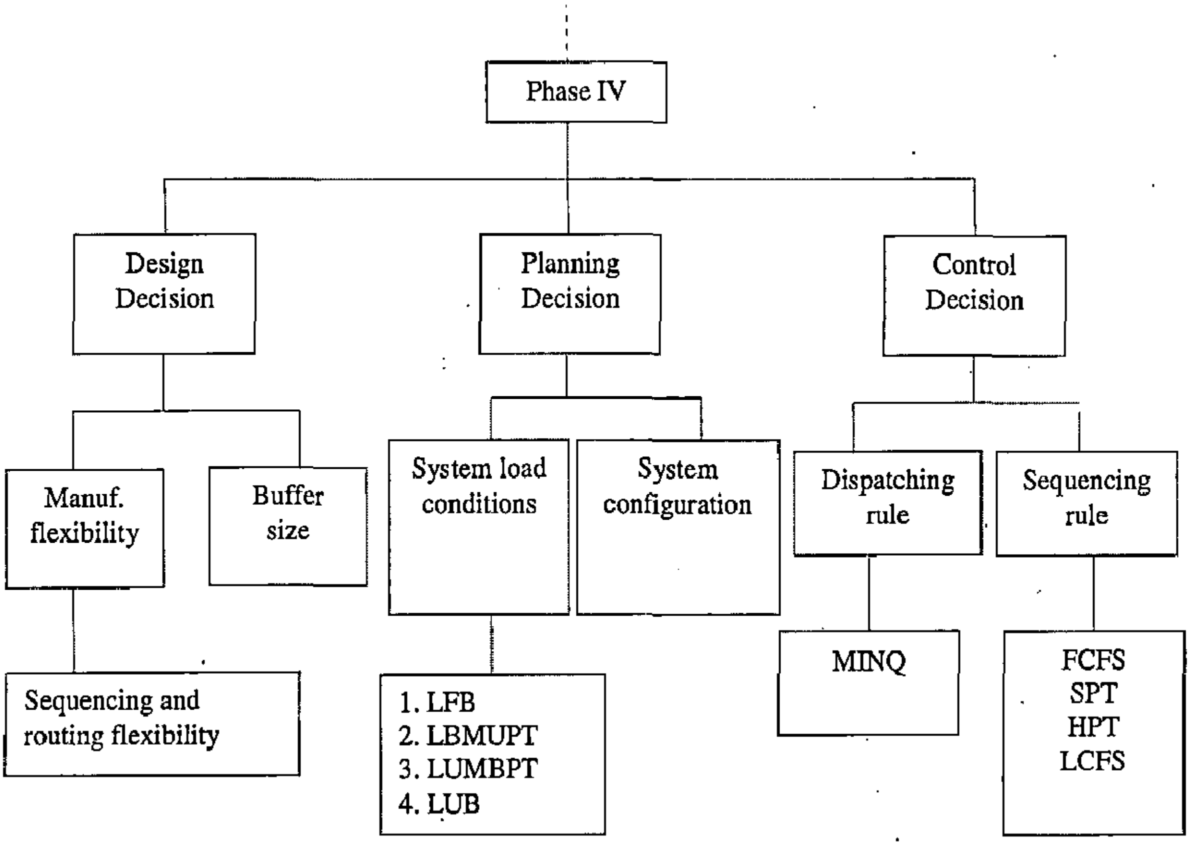
(b)


Phase II
Design Decision
Planning Decision
Control Decision
Manuf. flexibility
Buffer size
System load conditions
System configuration
Dispatching rule
Sequencing rule
Routing flexibility
1. LFB
2. LBMUPT
3. LUMBPT
4. LUB
MINQ
FCFS
SPT
HPT
LCFS

(c)


Phase III
Design Decision
Planning Decision
Control Decision
Manuf. flexibility
Buffer size
System load conditions
System configuration
Dispatching rule
Sequencing rule
AGVs
1. LFB
2. LBMUPT
3. LUMBPT
4. LUB
MINQ
FCFS
SPT
HPT
LCFS

(d)



(e)

Figure 3.1: Research Context

The design decisions include manufacturing flexibility, buffer size and number of AGVs in the systems. We try to find out how manufacturing flexibility (sequencing flexibility and routing flexibility) influence the makespan, work-in-process and resource utilization performance of SFMS and how does the buffer size modify this influence. We are also motivated to find out the impact of quantity of parts on the system performance, because it will help industry practitioners to decide on the suitable quantity of parts at which maximum benefit can be obtained. It was found during the review of literature on FMS and AGVs that the impact of flexibility in the FMS context need to be further enriched. Figure 3.2 shows the relation among the sub-systems in the FMS under stochastic environment. The need for automated material handling system evolved in response to the problems faced by traditional industrial automation. However, it is essential to integrate AGVs in manufacturing system before the design of a SFMS. Moreover the storage/buffer component is also to be integrated with SFMS for better scheduling of AGVs in the system. Figure 3.2 shows the flow of parts between different components of an SFMS. The effect of AGVs on system performance is considered in the fourth phase of system development (see Figure 3.1 (e).

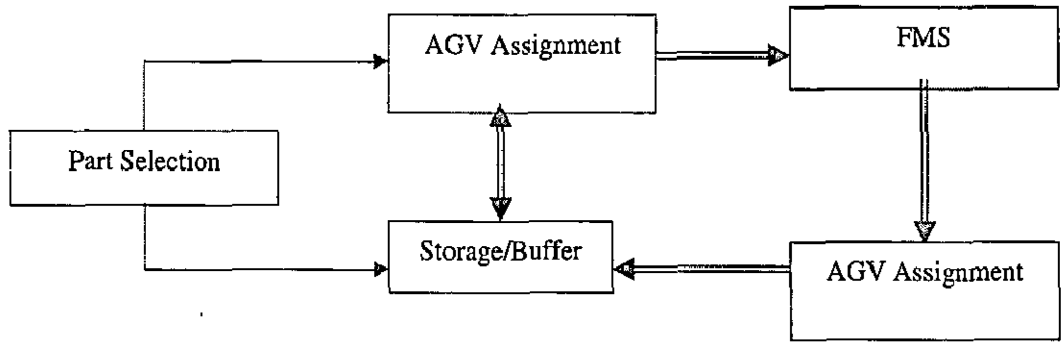


Figure 3.2: Integration between FMS with AGV

Planning decisions involves that the system operating under four different load conditions. These system load conditions are (a) Load Fully Balanced (LFB): The system operates under fully balanced machine load means that each of the machine as well as the total processing time of each part is fully balanced; (b) Load Balanced on Machine and Unbalanced Processing Time (LBMUPT): The system operates with full balanced machine load on each machine but the total processing time of each part type is not balanced; (c) Load Unbalanced on Machine and Balanced Processing Time (LUMBPT): The system operates with unbalanced machine load on each machine but total processing time of each part type is balanced and (d) Load Fully Unbalanced (LUB): The system operates with both machine load as well as total processing time of each part types is unbalanced. The other planning decision being considered is system configurations. We consider system configuration based on the location of buffers. SFMS consists of six machines having Dedicated Input Buffer (DIB) with finite capacity.

Literature review has shown that the system performance is highly dependent on control decisions that are implemented in the system. The control decisions are taken in the form of sequencing and dispatching rules. Four sequencing rules are used. These rules are First Come First Serve (FCFS), Shortest Processing time (SPT), Highest Processing Time (HPT) and Last Come First Serve (LCFS). The dispatching rule used is minimum number of part in the queue (MINQ).

3.2 Research motivation

In this thesis we are motivated to study the effect of design, planning and control decisions on the makespan, work-in-process and resource utilization performances of SFMS. From the literature review, the key research gaps have been identified. For instance, an important research gap is that, more attention is needed to study the combined impact of design, planning and control decisions on the performance of SFMS. From the research viewpoint, it is challenging because the flow of entity in the system become very difficult under stochastic environment when we model this domain. The overall relevance of this chosen area in the context of Indian manufacturing companies is very important. Since information based integration, automation and flexibility are costly, it is important to determine a proper choice of the various strategies under the SFMS designers' control.

We are also motivated to demonstrate the need to explicitly model the SFMS using simulation models. We aim to highlight important possible alternatives that may be of interest to SFMS designers/controllers while making the calculated investments. These works will the practitioners in identifying as what combinations of factors are likely to be beneficial. Similarly, it is important to point out which factors may prove counterproductive as well. The above mentioned factors outline our overall motivation towards this research effort.

At the shop floor, decisions and information have implicitly been assumed to be of real-time, like the Production Activity Control (PAC) module as stated by Baurer et al. (1991), considers real-time availability of information which helps to take control decisions. The time for information transfer and processing, decision making and implementation, has been assumed to be negligible. The operational level decisions in manufacturing systems are effective for a virtually real-time period to a few minutes or to even few hours. It is important to study the performance of the system under design, planning and control decisions implemented in real time.

In the next section we briefly outline some of the important research issues that may have important industrial implications and motivation.

3.3 Research issues

This thesis is aimed at enriching a research theme, focused on exploiting the design, planning and control decisions in the stochastic flexible manufacturing system. This system is considered as a discrete part manufacturing systems involving variety of product, towards achieving the improvement in makespan, work-in-process and resource utilization performance measures Wadhwa and Aggarwal, (2000); Wadhwa and Rao, (2004); Chan and Chan (2004); Wadhwa et al (2005); Ali and Wadhwa (2010) and

Joseph and Sridharan (2012). A salient contribution of this research effort is focused on adopting the concept of SFMS as a main domain of research.

Now, we present key research issues that have evolved around this theme. A theme of research, initiated by Wadhwa and Aggarwal, (2000), focused on the interaction between IT enabled automated integrated flexible system to improve the performance. Hence one can consider as an option provided by the system to take appropriate decisions to obtain the system objectives. Wadhwa and Rao, (2004) considered Decision-Information Synchronization (DIS) model in flexible systems. They showed that DIS has considerable effect on the lead-time performance in the flexible system. With the increase in the levels of flexibility, the lead-time reduces and hence performance of the manufacturing system improves. Chan and Chan (2004) considered that routing and sequencing flexibility are the important factors of an FMS. Routing flexibility helps to deal with short term conflict, such as breakdowns and changes in requirements by enabling material handling and on-line control (Barad and Sapir 2003). Routing decisions involve selecting the routes that should be followed by each part in the production mix to maximize use of resources utilization. Wadhwa et al. (2005) have studied the impact of sequencing flexibility to improve lead-time performance of manufacturing system. They performed series of simulation experiments in order to understand the underlying mechanisms. According to Ali and Wadhwa (2010), the importance of FMS has arisen due to their ability to produce customized products with shorter life cycles. They stated that large amount is needed to implement full flexibility in any of the systems, therefore a very careful decision is required for selecting the right type and right level of flexibility. In this work simulation and Taguchi's method is used to study the impact of design, planning and control decisions on FSIM performance. Furthermore, ANOVA is used to determine the most significant factor that contributes in improving the performance of the FMS. Joseph and Sridharan (2012) considered sequencing flexibility, routing flexibility and part sequencing rules in a perfect flexible manufacturing system. They considered tardiness and flow time of parts as the performance measures.

Within the context of SFMS we identified various research issues, to enrich the overall research theme. Computer simulation is selected to be an expedient platform to address these research issues. A primary motivation of the thesis is an attempt to demonstrate the need for explicitly modeling design, planning and control decisions in the SFMS.

Next, we briefly present some important research issues that have motivated this thesis. These are presented as interesting questions related to the SFMS domain.

- How do various sequencing flexibility levels impact the system performance under the influence of different system load conditions?
- How do various levels of routing flexibility impact the system performance under the influence of different system load conditions?
- Is the makespan, work-in-process and resource utilization performance of SFMS significantly superior at various levels of sequencing flexibility? Does the performance become comparable at various levels of sequencing flexibility? What will be the nature of performance variation on increasing the level of sequencing flexibility?

- Is the makespan, work-in-process and resource utilization performance of SFMS significantly superior at different level of routing flexibility? Does the performance become comparable at various level of routing flexibility? What will be the nature of performance variation on increasing the level of routing flexibility?
- Is sequencing flexibility and routing flexibility beneficial with increase in quantity of parts in the system? What is the suitable number of parts at which maximum benefit is obtained from the system? What is the nature of performance variation as the number of parts is increased in the system?
- What is the combined effect of sequencing flexibility and routing flexibility on the performance of SFMS?
- What is the effect of AGVs on the performance of SFMS?
- Do control decisions play an important role in the performance of SFMS?
- What are the industrial implications of the FSIM systems?

3.4 Research objectives

Keeping in view the research motivation and issues, we summarize the basic objectives. These objectives are as follows:

- To highlight the research motivation to study SFMS related to FMS under various design, planning and control decisions.
- To develop demonstrative models of the SFMS based on design, planning and control decisions.

- To study the sequencing flexibility (design decision) enabled makespan reduction, work-in-process reduction and increased resource utilization in SFMS operating under design, planning and control decisions.
- To study the routing flexibility (design decisions) enabled makespan reduction, work-in-process reduction and increased resource utilization in SFMS operating under design, planning and control decisions.
- To study the impact of combined effect of sequencing flexibility and routing flexibility on the performance of SFMS, operating under planning and control decisions.
- To study the effect of AGVs on the performance of SFMS under planning and control decisions.

3.5 Research Methodology

In this research the methodology being followed is shown in Figure 3.3. This model consists of conceptualization, simulation, analysis, synthesis and implementation. In the conceptualization phase, conceptual model was developed for the problem. In the simulation phase, simulation model was developed that defines the relationship among the variables. Finally the results were analyzed and synthesized with ANOVA. In this research, we have used computer simulation in ARENA simulation software due to the complexity of the problem. In an experiment one or more variables are used and their effects are measured in different performance measures in a stochastic environment. Initially few basic models were developed to focus the major issues of the SFMS i.e. sequencing flexibility model, routing flexibility model, combined sequencing flexibility and routing flexibility model and model for AGVs in SFMS. These basic models were used to experiment with the alternative planning, design and control decisions.

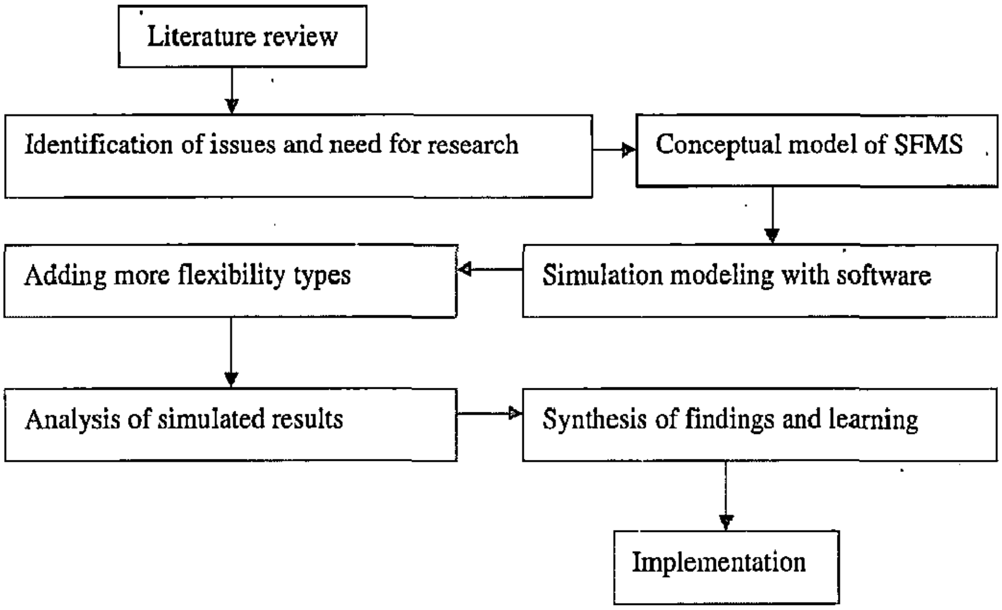


Figure 3.3: Research Methodology

Based on the important issues, the design of experiments was guided by one variable factor at a time. Thus the number of experiments required to fulfill the research objectives was indeed very large. Therefore a careful planning is required so that unnecessary experimental and possibility of confusions must be reduced. After performing all the experiments we applied Taguchi's experimental design for finding the best combinations among all variables. Here, the key methodological contribution is related to the approach wherein a complex problem was first reduced into smaller models and later the logical understanding of these models was used to assemble and make complex models. This approach has a lot of industrial relevance. This will help the researchers and practitioners to develop ways of translating his methodological guidelines effectively to modeling for large complex problems and their final analysis.

3.6 Conclusions

In this chapter, we have outlined the research methodology, motivation, issues and objectives. We have also presented the methodological approach to study the objectives outlined. The demonstrative model of SFMS in the domain of FMS was developed to provide the insight on the behavior of key factors. We focused on phase development of SFMS by considering design, planning and control decisions so as to determine, how that decisions affects the performance of the system. Simulation technique is found to be suitable for study of this nature involving so many variables interacting with each other in a complex manner. In the next chapter we have discussed the development of conceptual framework for SFMS.

Chapter 4

Development of Conceptual Framework of SFMS

4.1 Introduction

Substantial research efforts have been dedicated to the development of various manufacturing decisions systems for FMS having real-time shop floor control at the operation levels. The GRAI (Graph with Results and Action Interrelation) presents this focus in its macro reference model very clearly (Doumeingts et al. 1995). The model shows that the manufacturing system is comprised of three sub-systems i.e. decision, information and physical system as shown in Figure 4.1.

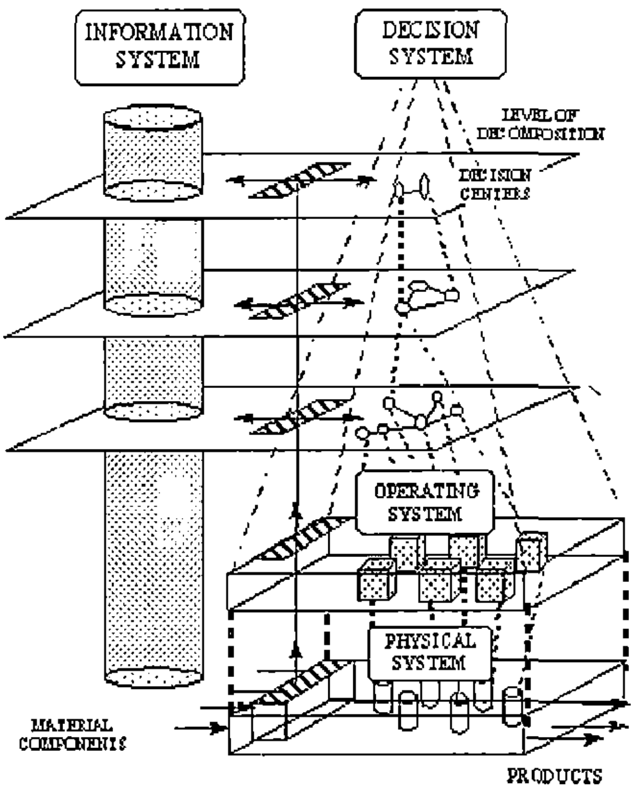


Figure 4.1: GRAI macro reference model (Doumeimgts et al. 1995)

In this model the decision system represents a hierarchical structure. The information infuses through the entire system. It provides the relevant link between decision and operating system. The physical system represents the manufacturing unit that comprises of machine, material and operating system. This GRAI model helps us in the implementation of design, planning and control decisions at operational level of Stochastic Flexible Manufacturing System (SFMS). In most of the manufacturing systems especially in FMS the time for collection, processing and transfer of information as well decision making and implementation is assumed to be negligible. GRAI model help to analyze the information, decision and physical systems with their related activities and events explicitly in modeling SFMS. GRAI model further outlines the role of timely decision making, particularly at operating levels, as these decisions at this level may be valid for a very short interval.

In view of the above discussion now it is a need to study the performance of SFMS under different decisions like design, planning and control. We stress on the significance of these decisions in the modeling for designers, who look to develop suitable decisions to take advantage of available flexibility for improvement in the system performance. In this research we conceptualize the demonstrations of some essential design, and planning decisions with their impact on control decisions at shop floor level in SFMS.

In the designing of SFMS we assume a fully automated decision system that is capable of making decision in real time perspective. It is useful to view a SFMS in terms of three types of decisions, which control its development over any time sphere as a discrete event system. There are events related to the starting and finishing of information, decision and the physical related activities.

Figure 4.2 shows the conceptual framework of the proposed manufacturing system i.e. stochastic flexible manufacturing system.

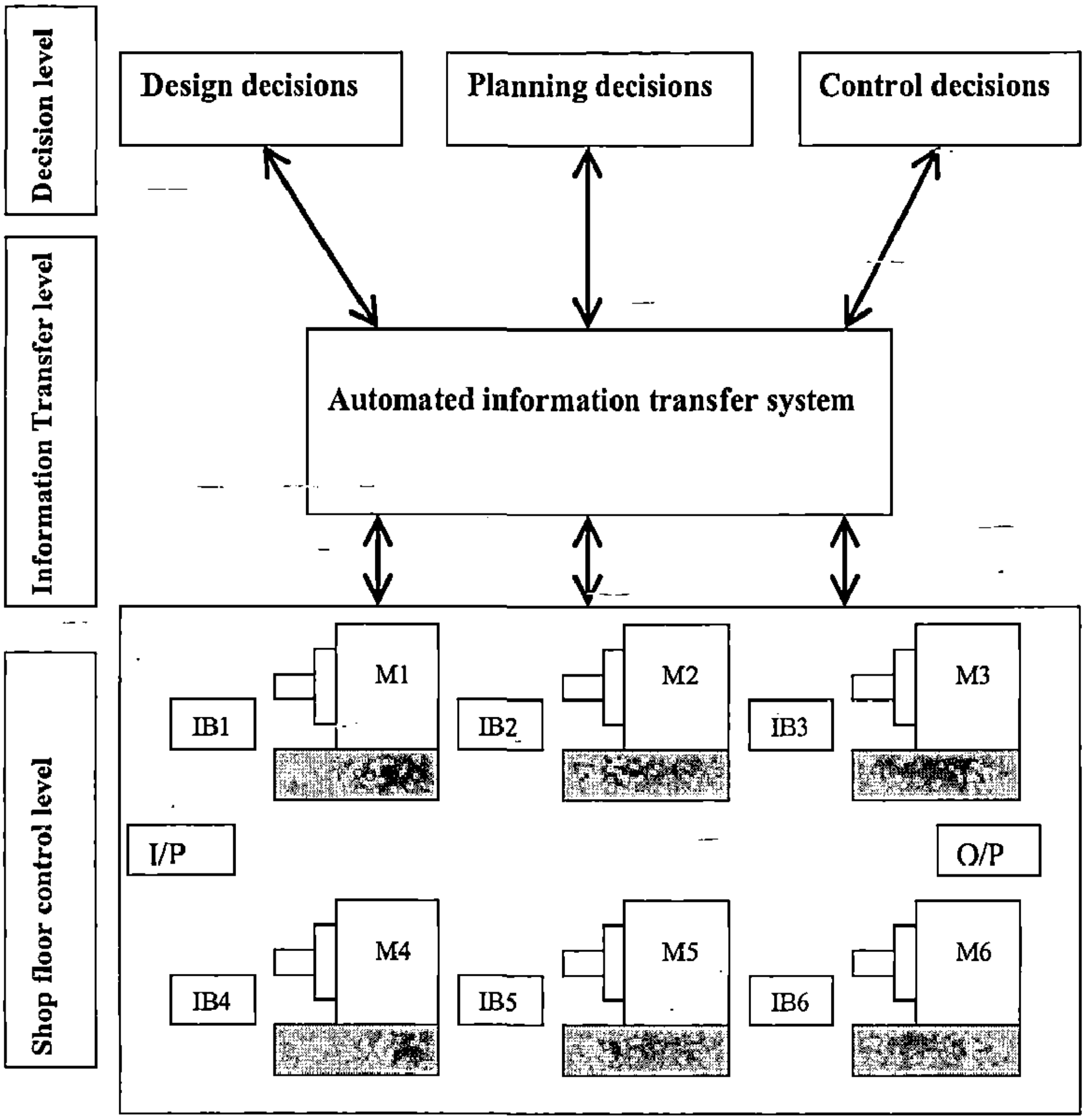


Figure 4.2: Conceptual Framework of SFMS

This is to be divided into three levels i.e. decision level, information transfer level and shop floor control level. The figure shows the levels of GRAI model that discussed earlier. At the shop floor level we have machines, machine buffers, material, operators etc. while at information transfer level we have computers that process the received information and transfer to the relevant units. The top most level represents the various decisions norms namely designing, planning and controlling decisions.

Figure 4.3 shows the detail of SFMS conceptual model. The various decisions to be taken are our prime concern in this research work. In this work, the SFMS are modeled as discrete event system. Therefore discrete event simulation modeling techniques have been used for the study of various decisions in SFMS. It will be quite useful for the researchers to study the SFMS by changing one factor at a time. But the approach involved in the simulation of model where one factor is changed at a time is not very much accepted for many of the researchers. Therefore the number of possible factor level combinations increases as the number of factors increases. The key concerned of practitioners/managers is to obtain immediate understanding of the interaction of key factors and their relative contributions under its control. In this research work our emphasis is to demonstrate the importance of explicitly model different decisions namely designs, planning and control in stochastic manufacturing environment.

4.2 Defining a sample manufacturing system

The aim of this work is to find the effect of alternative design, planning and control decisions in the system. A demonstrative model is developed to help both the researchers/practitioners to take appropriate decisions. We have seen from the literature that most of the researchers considered 4 to 6 machine and 3 to 6 part types for the development of simulation models for the manufacturing system. The literature shows that many of the researchers have considered deterministic simulation model so in view of the above we tried to develop stochastic simulation model that is somehow close to the real system. The processing time is taken as normal distribution while the transportation time between the stations is considered as the exponential distribution. From literature review we have selected a sample manufacturing system whose key features are now describe.

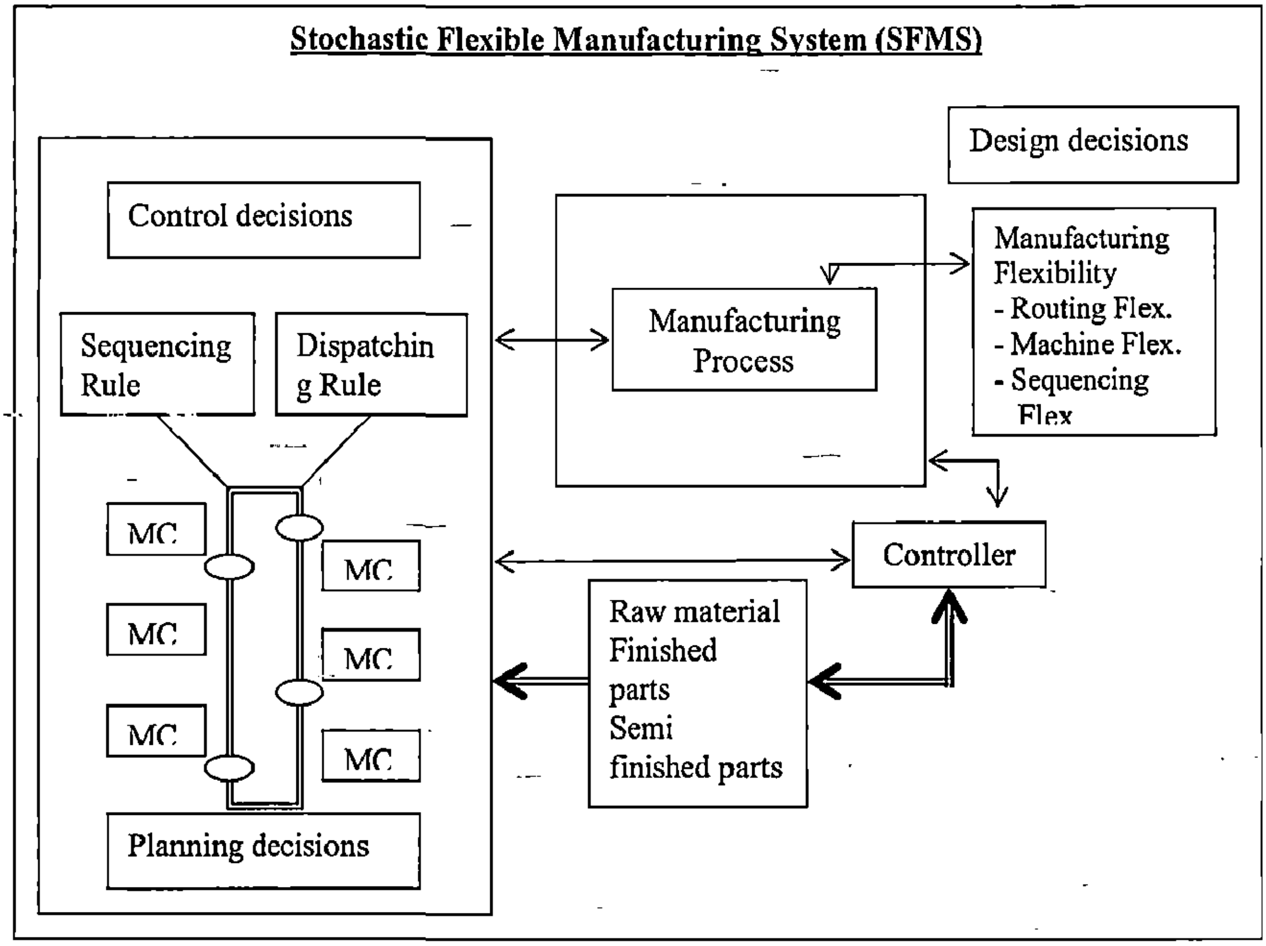


Figure 4.3: Detail Conceptual Framework of SFMS

4.2.1. Key features of the sample system

In this research work we developed the conceptual framework of the Stochastic Flexible Manufacturing System (SFMS). Two types of flexibilities are considered i.e. sequencing flexibility and routing flexibility. The system is comprises of six machines with dedicated input buffer of variable size. For simulation 600 parts are manufactured with 6 parts type of equal ratio i.e. 100 of each type. Five operations were considered for each part. The operation time is taken from the real manufacturing system under four different load conditions i.e. LFB, LBMUPT, LUMBPT and LUB as shown in Tables 4.1 to 4.4.

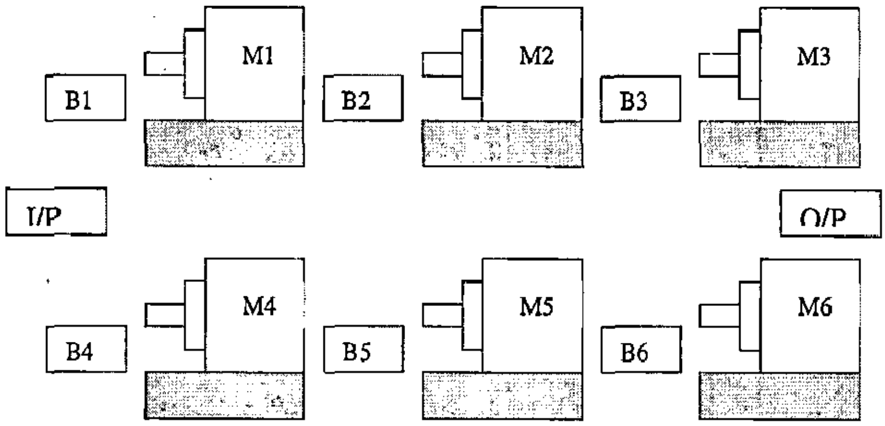


Figure 4.4: Sample manufacturing system

As we are studying the stochastic environment therefore this real data is converted into normal distribution and the mean and standard deviation are given with the corresponding tables. Four flexibility levels of sequencing flexibility (i.e. SF0, SF1, SF2 and SF3) and routing flexibility (i.e. RF0, RF1, RF2 and RF3) with four parts sequencing rules (i.e. FCFS, SPT, HPT and LCFS) were considered for the study. The performance of the SFMS was evaluated using make-span time, work-in-process and resource utilization. Each model has six identical and flexible machines M1, M2, M3, M4, M5 and M6. All these machines have dedicated input buffers with variable capacity of holding 5, 10, 15 and 20 parts. Figure 4.4 shows the sample stochastic flexible manufacturing system.

4.3 Development of SFMS

Flexibility may be classified as hardware flexibility and software flexibility Blackburn and Millen (1986). Routing flexibility falls under hardware flexibility. In routing flexibility there are options of selecting among the potential machines. In contrast of it sequencing flexibility is considered as software flexibility. Sequencing flexibility is exploited when the operations can be performed in different orders. It can only be possible if there is no precedence relationship between the operations. Hence sequencing flexibility depends on the type of product therefore it can be exploited in conventional as well as in flexible manufacturing systems. But however, sequencing flexibility is not very much exploited.

4.3.1. Modeling sequencing flexibility

The parts were sequenced according to the sequencing flexibility. The measure of sequencing flexibility was considered as proposed by Rachamadugu et al. (1993). Illustration of sequencing flexibility is shown in Figure 4.5. The make-span, work-in-process and resource utilization for processing a product-mix of 600 parts are considered as performance measures.

Sequencing flexibility depends on the type of product to be produced. It is exploited if there is no dependency of operations on each other. The maximum flexibility can be achieved when all the operations are independent that is none of the operation has any precedence. Hence the sequencing flexibility is measured on the bases of number of possible operation sequences in a job (Sethi and Sathi 1990). Rachamadugu et al. (1993) proposed sequencing flexibility measure that is defined as:

$$SFM_i = 1.0 - \frac{2^* \ TPA_i}{n_i\,(n_i - 1)} \tag{4.1}$$

Where

n_i = number of operations for part i,

TPA_i = number of transitive precedence arcs in the operation graph for part i

The transitive precedence arc represents the precedence relationship between the pair of all operations, both explicit and implicit of a part. Figure 4.5 shows the operation graph of sequencing flexibility level 2. Figure 4.6 shows four explicit precedence arc that are (1,2), (2,4), (3,4), and (4,5). There are four implicit precedence arc between operations (1,4), (2,5), (1,5) and (3,5). Therefore the total number of precedence relationships are 8 i.e. TPA equals to eight.

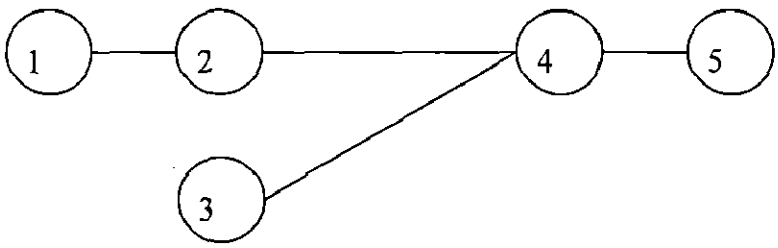
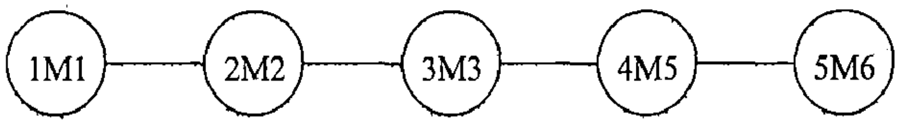


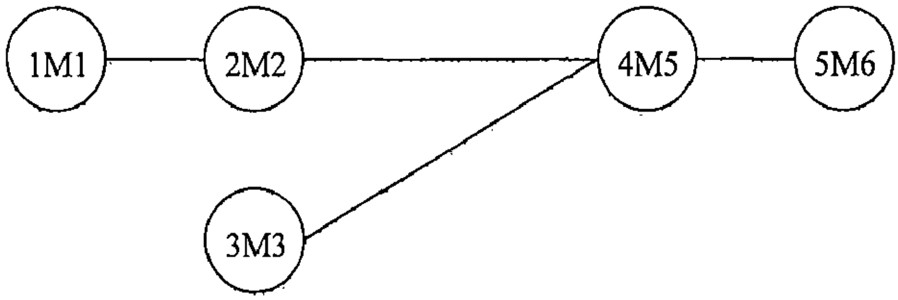
Figure 4.5: Operation graph of sequencing flexibility level 2.

Therefore for the given operation graph the sequencing flexibility measure value is 0.2 by using the above equation. With the above equation the value of sequencing flexibility is 0 if there is no flexibility where as it is 1 if the system have full flexibility. Here one of each type of operation graph is shown in the figure 4.4 along with its flexibility measure.

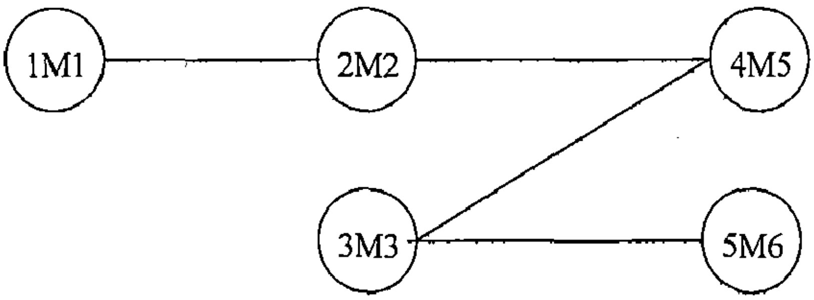
$$SF0 = 1 - \frac{2(4+6)}{5(5-1)} = 0.0$$



$$SF1 = 1 - \frac{2(4+4)}{5(5-1)} = 0.2$$



$$SF2 = 1 - \frac{2(4+1)}{5(5-1)} = 0.5$$



$$SF3 = 1 - \frac{2(0+0)}{5(5-1)} = 1.0$$

Figure 4.6: Operation graphs at four sequencing flexibility levels (Rachamadugu et al 1993).

The schematic diagram showing the flow of material and information in SFMS is depicted in figure 4.7. Initially the parts were created in the controlled manner and moved to the loading area to run the simulation model. The loading area receives the information from the out flow point to release a part for the manufacturing system. The part after being released from the loading area, were consecutively sent to the decision area. Here the decision regarding the part type is taken. On the basis of the part type, the parts were sent to respective machine where the required attributes were assigned to the part. Then the information related to status of the machine buffer was obtained. If the capability of the machine buffer BC is less than the specified value say C, then the part moves in the buffer.

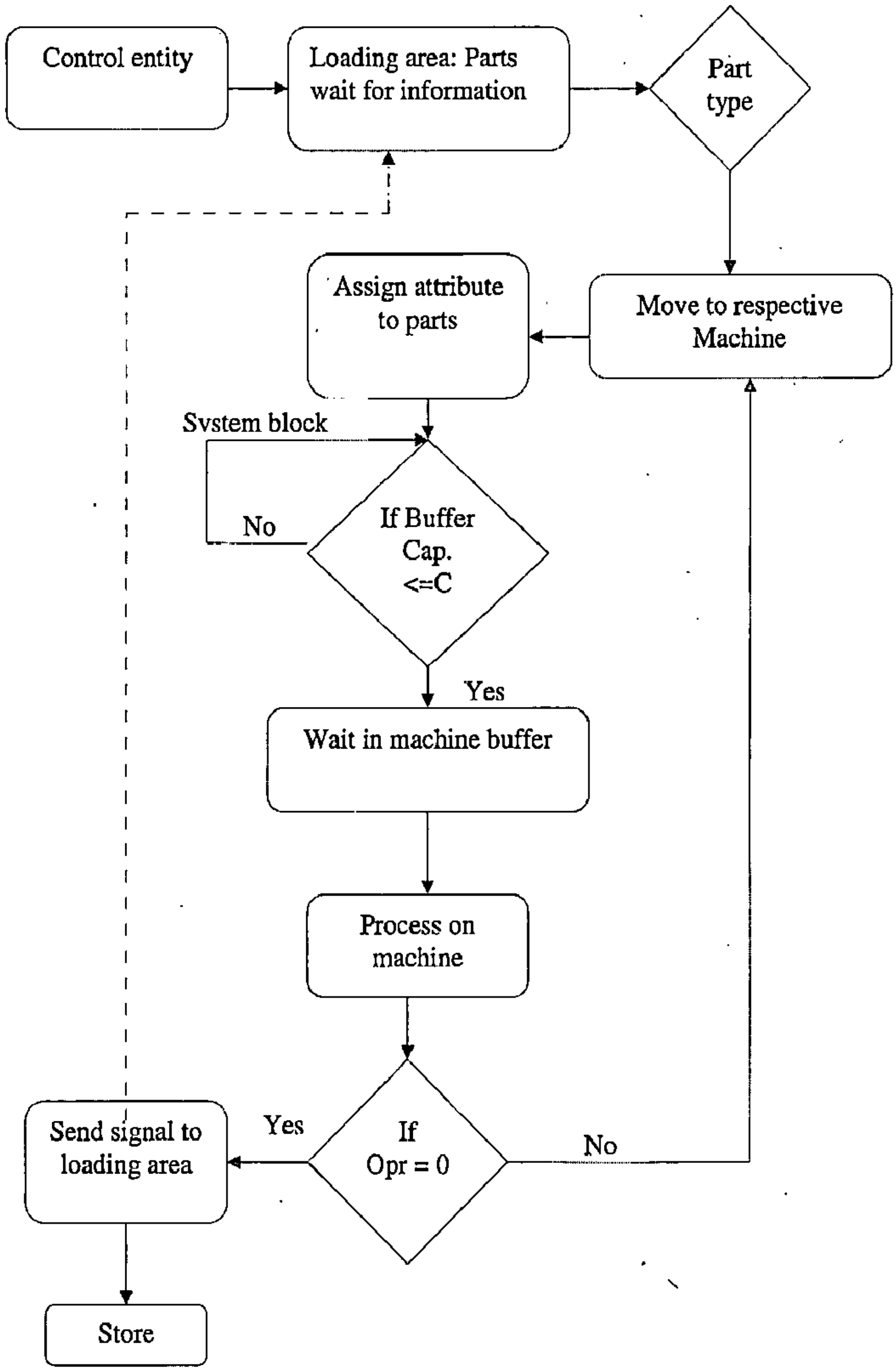


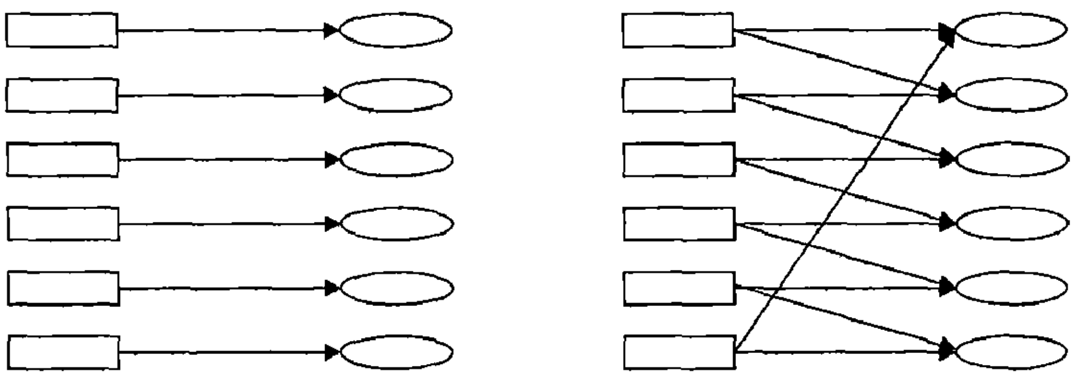
Figure 4.7: Schematic diagram depicting flow of materials and information in the system with sequencing flexibility

If the capability of the machine buffer is full, then the system blocks. The parts wait in the buffer until the machine become free. As the part processed and moved out from the machine then the next part entered into the machine. Once the parts have been completed its process on one machine, it is being sent to the next decision point. At this decision point, a decision is made to find out whether the part is completed all its operations or not. If it completed all the operations, it is disposed off from the system. If any of the operation is remained to be done. The part moved to the next required machine, where its attributes are updated. If a part is completed of all its operations it is sent for storage. Before going to the store, the part sends a signal to the loading area to release the same part from the control entry system. In this way, a constant number of parts are maintained in the system. This cycle of activities repeats until all the parts have been processed.

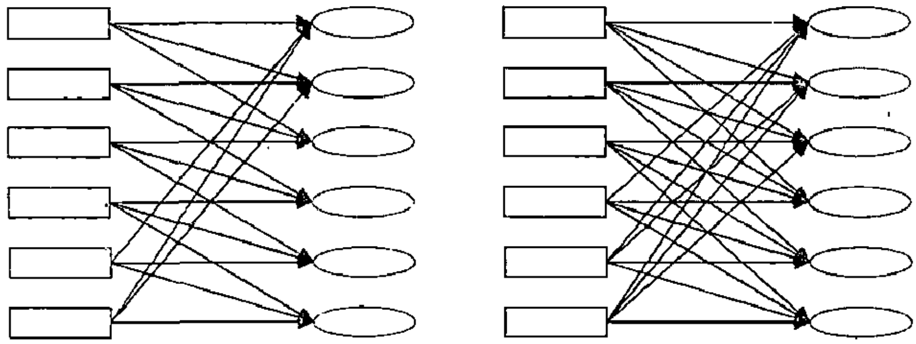
4.3.2 Modeling routing flexibility

This study is performed in a stochastic environment of a flexible manufacturing system with six identical flexible machines i.e. M1, M2, M3, M4, M5 and M6 along with an input buffer with each machine. Six part types were considered i.e. P1, P2, P3, P4, P5 and P6. For each of the parts five different operations were considered. Barad et al. (2003) have stated that with routing a part can move through different routes to process by alternative machines. We will use this measure of routing flexibility in the present thesis.

RF=0, means that there is one to one relationship between machine and the part i.e. there is no alternative route for the parts. At RF=1, one operation can be done on two machines i.e. there is 1 more alternative machine for the same job (in addition to the machine available at RF=0). At RF=2, means that for one operation there are three possible alternative machines i.e. there is 1 more machines is available for processing the same operation (in addition to the machines available at RF=1). Similarly for RF=3 and RF=4 mean 3 and 4 alternative machines are available respectively for any part or operation. Figure 4.8 shows the illustration of how routing flexibility is achieved as given by Wadhwa and Rao (2004). Routing flexibility at level 2 is further elaborated in Figure 4.9. This figure shows the flow of part 1 at second level of routing flexibility. Similarly all the six parts are moved between the machine stations. Solid arrows are shown the first option for the part 1 after completion of each operation on the respective machine and the dashed arrows are used to show the second option for the corresponding operation.



(a) RF=0 (b) RF=1



(c) RF=2 (d) RF=3

Figure 4.8: Schematic diagrams of four levels of routing flexibility (Wadhwa and Rao2004)

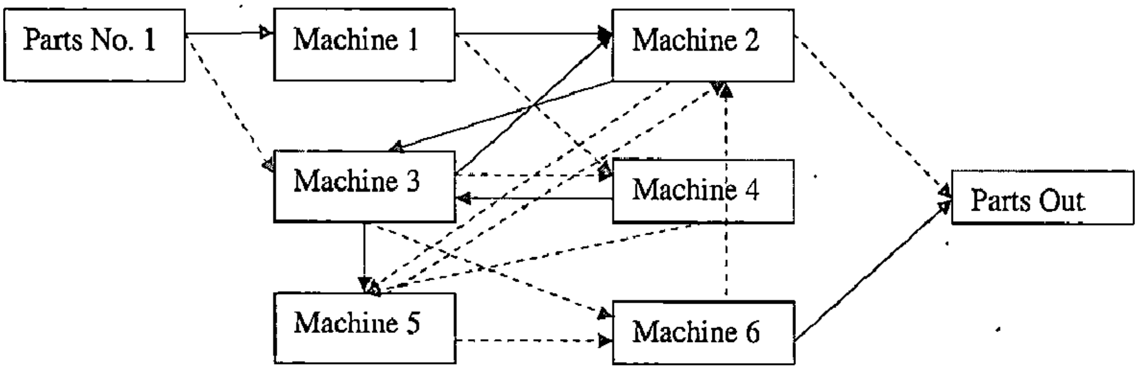


Figure: 4.9: Flow of Part 1 at RF1

The schematic diagram showing the flow of material and information in routing flexibility based SFMS is shown in the Figure 4.10. Initially the parts ware created in the controlled manner and moved to the loading area to run the simulation model. The loading area receives the information from the out flow point to release a part for the system. After the part has been released its identification is made. On the basis of the part type, parts are sent to the potential machine for performing the respective operation. Then the information is obtained to know the status of the machine buffer. If the buffer is capable of holding the part, the part in turn goes to the buffer of that machine and the required attributes were assigned to the part. If number of parts in the machine buffer are equal to the capacity of the buffer then the part finds another route. If the capacity of the machine buffer is full in the last option, then the system blocks. The parts wait in the buffer until the machine become free. As the part processed and moved out from the machine the next part enters on the bases of queue sequencing rules. Parts after being processed on a particular information is obtained to know whether all the operation of that part has been completed or not. If all the operations are completed, then the part is moved to the store. If any of the operation is left to be done then the part is moved to the respective machine, where its attributes are updated.

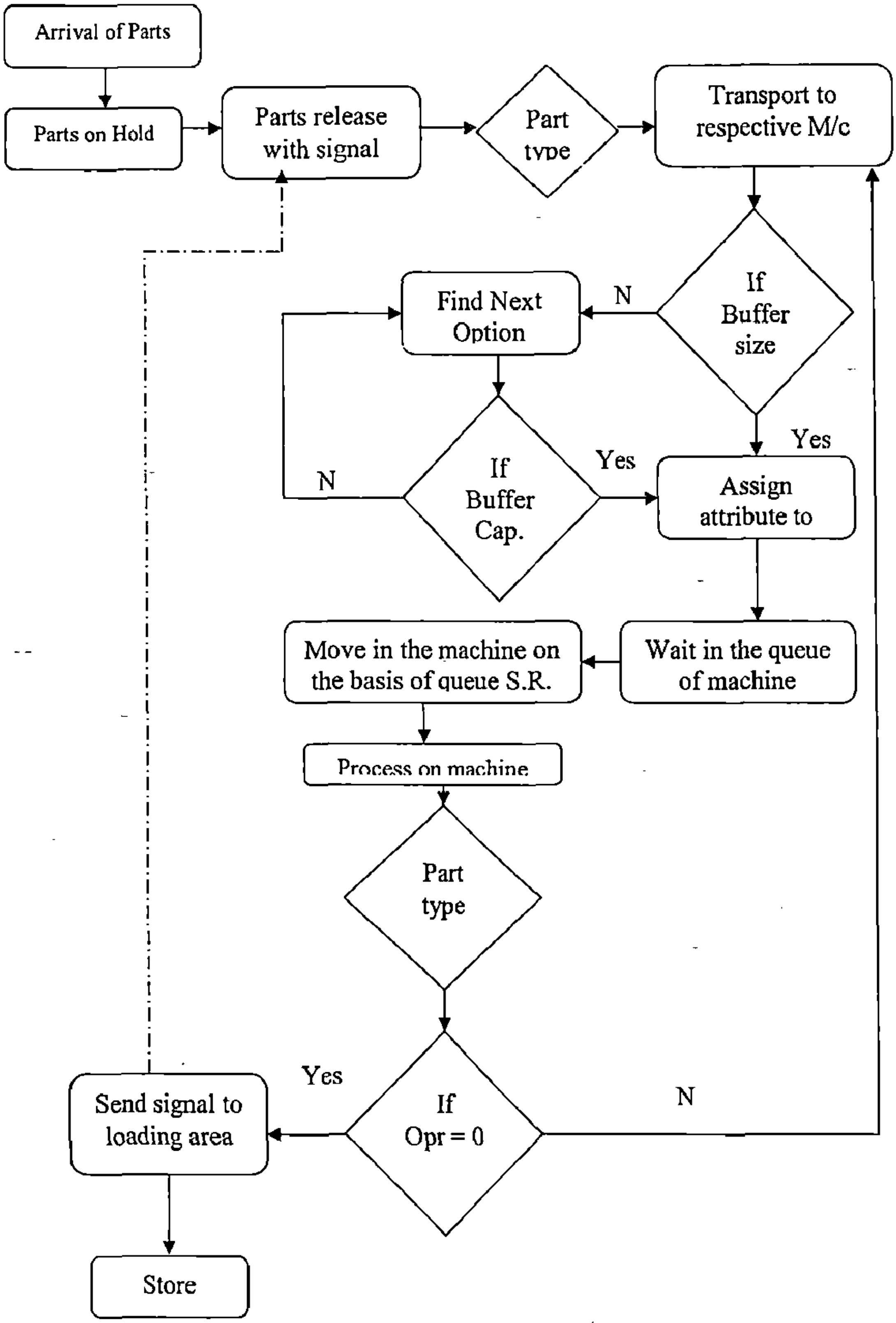


Figure 4.10: Schematic diagram depicting flow of materials and information in the system with routing flexibility

Once all the operations on the part are completed it is sent for the storage. The information is sent in the form of signal to the loading area releasing the same part from the control entry system. In this way, a constant number of parts are maintained in the system. This process goes on until all the parts have been processed.

4.4 Assumptions

The aim of this study was to determine the effect of design, planning and control decisions on the performance of SFMS. It is assumed that the processing time of the parts is considered as normally distributed with four different system load conditions that are mentioned in the above section and four sequencing rules. The system capacity is controlled by maintaining the input buffer size of each machine. Sequencing rules are employed over each queue of the machine individually. The make-span, work-in-process and resource utilization are considered as the performance measure. One operation is performed on a machine at a time. Processing time also includes the set-time.

In the first phase development of SFMS four decision factors are considered and each of the factors has four levels. These decision factors are changed in each simulation run in order to obtain the best combination factors. The four factors are sequencing flexibility (SF), system capacity (SC), system load (SL) condition, and sequencing rule (SR). Sequencing flexibility has four levels. In the second phase in place of sequencing flexibility, routing flexibility is applied keeping all other factors same. In the third phase AGVs are used with the first level of sequencing/routing flexibility. In the fourth phase the combined effect of both sequencing and routing flexibility is applied. Four part volume are selected i.e. P6, P12, P18 and P24 by the control entry system which means that the numbers of parts in the system at a time are 6, 12, 18, and 24. The simulation experiments are performed with four different load conditions, i.e., load fully balanced (LFB), load balanced on machine and unbalanced processing time (LBMUPT), load unbalanced on machine and balanced processing time (LUMBPT) and load fully unbalanced (LUB). The fourth factor is sequencing rules that are used for controlling the sequence of parts in the input buffer of the machine. All the decision factors with their levels are shown in Tables 4.1, 4.2, 4.3 and 4.4. Hence, for all the studies there are four factors with four levels that controls the performance of SFMS.

Table 4.1: Factor-level details for sequencing flexibility (First Phase)

Factor	Factor level	Level Id.
Sequencing flexibility (SF)	0	1
	1	2
	2	3
	3	4
System capacity (SC)	30	1
	60	2
	90	3
	120	4
System load (SL)	LFB	1
	LUB	2
	LUMBPT	3
	LBMUPT	4
Sequencing rules (SR)	FCFS	1
	SPT	2
	HPT	3
	LCFS	4

Table 4.2: Factor-level details for routing flexibility (Second Phase)

Factor	Factor level	Level Id.
Routing flexibility (RF)	0	1
	1	2
	2	3
	3	4
Part Volume in system	30	1
	60	2
	90	3
	120	4
System load (SL)	LFB	1
	LUB	2
	LUMBPT	3
	LBMUPT	4
Sequencing rules (SR)	FCFS	1
	SPT	2
	HPT	3
	LCFS	4

Table 4.3: Factor-level details for AGV model (Third Phase)

Factor	Factor level	Level Id.
No. of AGVs	1	1
	2	2
	3	3
	4	4
Velocity of AGVs (m/s)	2	1
	4	2
	6	3
	8	4
System capacity (SC)	30	1
	60	2
	90	3
	120	4
Sequencing rules (SR)	FCFS	1
	SPT	2
	HPT	3
	LCFS	4

Table 4.4: Factor-level details for combined sequencing and routing flexibility (Fourth Phase)

Factor	Factor level	Level Id.
Flexibility Type and Level		
SF3	1	1
RF1	2	2
SF3RF1	3	3
System capacity (SC)	60	1
	90	2
	120	3
Sequencing rules (SR)	FCFS	1
	SPT	2
	HPT	3

4.5 Development of simulation models

The simulation model of SFMS has been developed in ARENA simulation. The ARENA simulation package provides a good graphical interface and animation utilities. At the same time it does not have any explicit feature for modeling a flexible system. We developed the three simulation models i.e. sequencing flexibility model, routing flexibility model and AGV model with stochastic environment.

The proposed stochastic flexible manufacturing systems are run at different system load conditions. These are as follows:

(1) Load Fully Balanced (LFB): The system operates under fully balanced machine load means that each of the machines as well as the total processing time of each part is fully balanced;

(2) Load Balanced on Machine and Unbalanced Processing Time (LBMUPT): The system operates with full balanced machine load on each machine but the total processing time of each part type is not balanced;

(2) Load Unbalanced on Machine and Balanced Processing Time (LUMBPT): The system operates with unbalanced machine load on each machine but total processing time of each part type is [illegible]balanced and

(4) Load Fully Unbalanced (LUB): The system operates with both machine load as well as total processing time of each part types are unbalanced.

The same system is modeled for the above four system load conditions. Appendix A, (Table A1 to A4) shows the processing time and machine load, when operated under the alternative system load conditions. In stochastic modeling the processing time may vary from one model to another with the influence of many factors, but here it is assumed as normally distributed. Ozcan et al. (2011) considered task times are stochastic variables independently distributed with normal distribution and they ignored the travel times. The mean and standard deviation of each load conditions are given along with the respected tables.

The sequencing rules helps to select the parts on the basis of priority from the buffer of the machine. The sequencing rules are modeled as follows:

(a) First-come-first-served (FCFS): the parts were selected from the buffer on the basis of first come-first-served.

(b) Shortest processing time (SPT): the parts, having the shortest processing time, were selected for processing first from the buffer of the machine.

(c) Highest processing time (HPT): the parts, having the highest processing time, were selected for processing first from the buffer of the machine.

(d) Last-come-first-served (LCFS): the parts were selected from the buffer on Last-come-first served basis.

The machines were selected on the basis of dispatching rule. One dispatching rule that is MINQ rule is used. This rule helps to select the machine on the basis Minimum Queue of parts at the input buffer.

4.6 Verification and validation of simulation model

Schlesinger et al (1974) described the verification as "the process of confirming, that the conceptual model has been correctly converted into an operational computer program and the calculation within the programme utilize the correct input data". The importance of verification of simulation model is to ensure that the model is performing as the specified performance.

In the present work, verification of the simulation model is carried out with the help of inbuilt features of ARENA package and also by continuous monitoring of the important variables of the system. When the model runs the parallel SIMAN coding generated. This coding helps as quick references for verification of the simulation model. Another important aspect of simulation is the validation of the model. The validation of this model is done according to the approach by Fryer (1973) that hypothetical simulation model should perform according to the assumption and logic developed for the model. This is achieved by tracking the movement of parts step by step of the simulation run to validate the model performance.

4.7 Conclusion

In this study, the simulation model of SFMS has been developed in ARENA simulation package. The proposed flexible manufacturing system i.e. SFMS consists of 6 flexible machines with dedicated input buffer for each machine. The system produces 6 part types with 5 operations for each part. The processing time is taken as random variable with normal distribution. The mean and standard deviation for each load condition are given with the respected data tables. Design decisions considered are sequencing and routing flexibility, buffer size and number of AGVs. Planning decisions includes system load conditions, system configurations and batch size. Control decisions manifests in the form of sequencing and dispatching of parts in the system. In this work velocity of AGVs is also considered under control decisions of AGVs. The simulation model of SFMS has been verified with the help of facilities available in ARENA package. With the help of simulation models a series of experiments are conducted in different stochastic conditions. The results are presented and discussed in Chapter 5, 6, 7 and 8.

Chapter 5

Performance of SFMS under Sequencing Flexibility

5.1 Introduction

In Chapter 3, we have stated the main objectives of this thesis. The objectives are to enrich stochastic flexible manufacturing system (SFMS) in the domain of FMS operating with different design, planning and control decisions. All these decisions are implemented in phased manner. In the first phase design decisions considered is sequencing flexibility and system capacity (buffer size), planning decisions include different system load conditions and system configurations and control decisions include dispatching and sequencing rules. In Chapter 4, based on the motivation and objectives as stated in Chapter 3, we developed the conceptual model for SFMS.

This chapter presents the experimental results obtained through simulation. Three important decisions are used for performing experiments. Design decision considered are four sequencing flexibility levels (SF0, SF1, SF2 and SF3) and system capacity level is kept at 120 (at a time120 no. of parts in system). Planning decision include four system load conditions (load fully unbalanced (LUB), load fully balanced (LFB), load balanced on machine and unbalanced processing time (LBMUPT) and load unbalance on machine and balanced processing time (LUMBPT). Control decisions include four sequencing rules (FCFS, SPT, HPT and LCFS) and one dispatching rule (MINQ). The performance of the system is evaluated using performance measures such as make-span time, work-in-process, and average resource utilization. The stochastic environment was developed by providing normal distribution for processing time, and exponential distribution for inter-arrival time of parts in the system. The processing time and their respective mean and standard deviation are given Appendix A (Table A1 to A4). The sequence of operations for all the parts operating under different load conditions and sequencing flexibility levels are shown in the Appendix 'B' (Table B1 to B4).

Simulation model for SFMS was developed in Arena simulation software. The developed models are used to conduct a series of experiments to investigate the effects of sequencing flexibility, system capacity, system load conditions and part sequencing rules. In the stochastic environment of a SFMS the simulation experimentation first involves determining the study data set. For this a number of experimental sets were performed with different number of replications in each set (i.e. number of replications per set 5, 10, 15, 20, 25) as shown in figure 5.0.

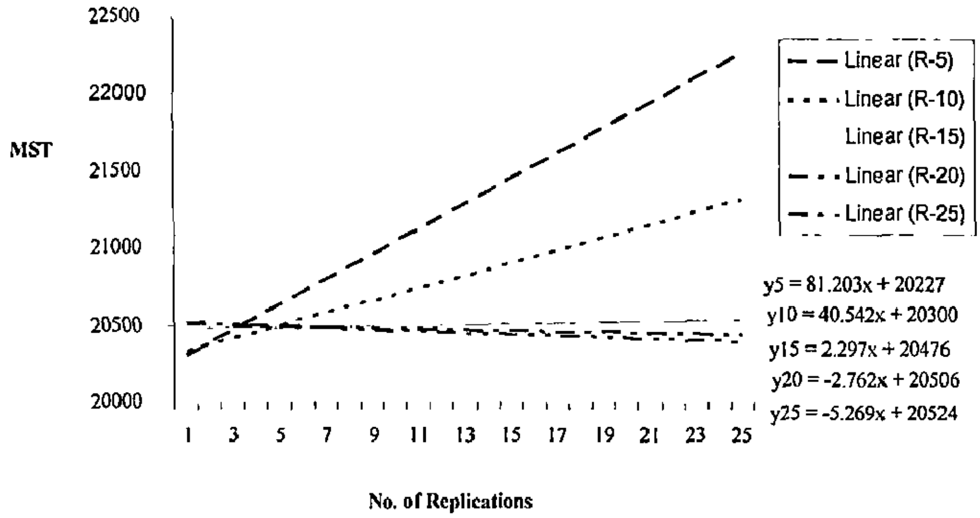


Figure 5.0 Slope for different number of replications

In the above set of experiments it is observed that at 15 number of replication the data slope was almost uniform where as the slope increases in the positive direction as the number of replications decreases and the slope increases in the negative direction when there is increase in the number of replications from 15. So in view of the above observations it was decided to take 15 replications for each set of experiment. The average of the results obtained from 15 replications is used for analysis purpose.

5.2 Simulation results under sequencing flexibility

As stated earlier SFMS is developed under phased manner. In the first phase we consider sequencing flexibility as design decision. The impact of sequencing flexibility on the performance of SFMS is evaluated under different planning and control decisions as shown in the figure 5.1.

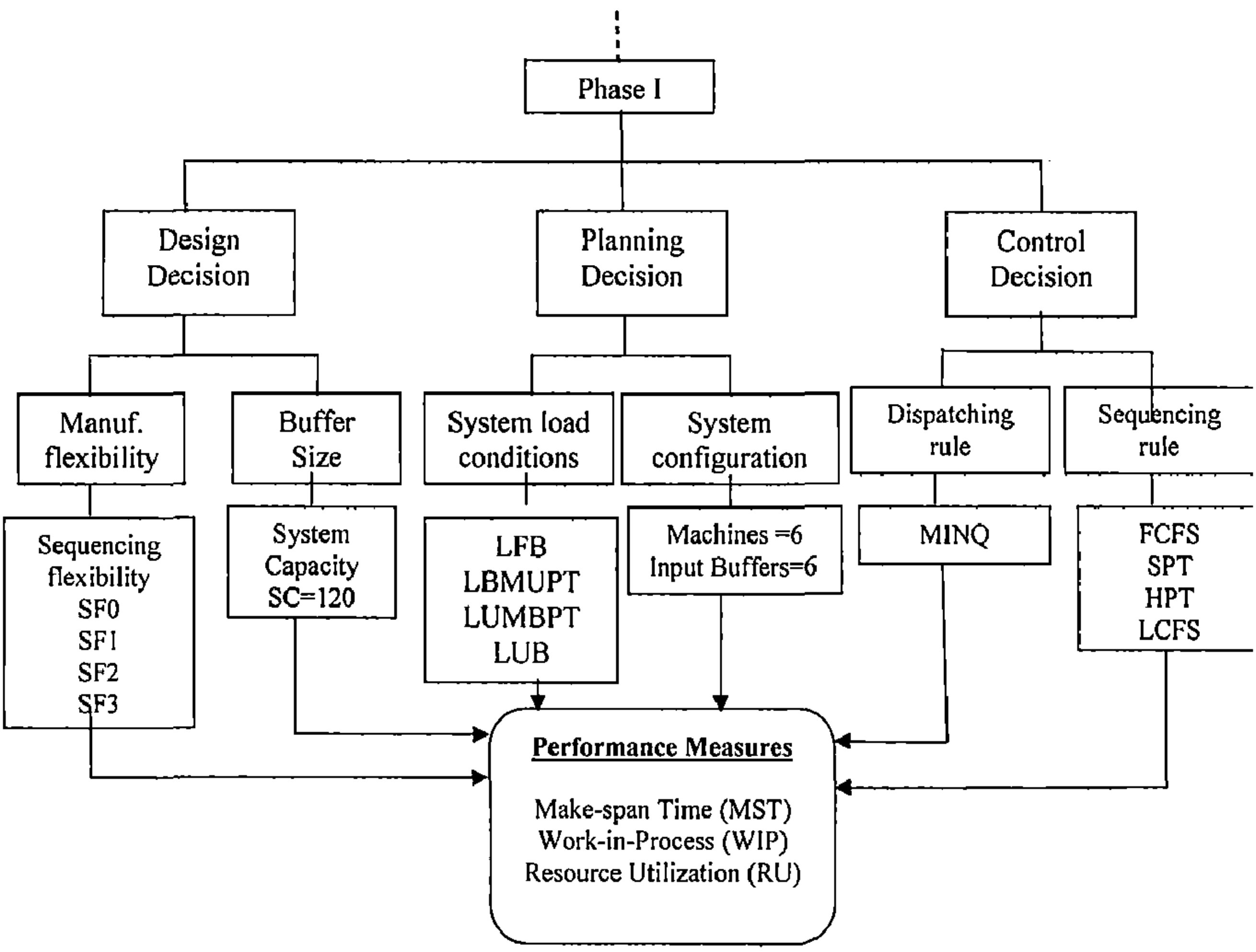


Figure 5.1: Salient features of the study of phase I

5.2.1. Effect of sequencing flexibility on MST at different system load conditions

In this section we find the effect of sequencing flexibility on make-span time (MST) at different system load conditions. The figures 5.2 to 5.5 are drawn between MST and sequencing flexibility at all four system load conditions. Tables 5.1 to 5.4 shows the MST value at four levels of sequencing flexibility under four system load conditions and four sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively.

Figure 5.2 shows the impact of sequencing flexibility under different load conditions at sequencing rule FCFS for 600 parts at a system capacity of 120 on the MST performance of the system. It is seen from the figure that at SF0, MST is maximum for LUB and minimum for LUMBPT. At SF1, again MST is maximum for LUB and minimum for LBMUPT. At SF2, MST is maximum for LUB and minimum for LFB. Similarly at SF3 it is observed that MST is maximum for LUB and minimum for LFB. As one adopts different levels of sequencing flexibility, MST decreases from SF0 to SF3 for LUB system load condition. Almost similar trend is observed for other system load conditions.

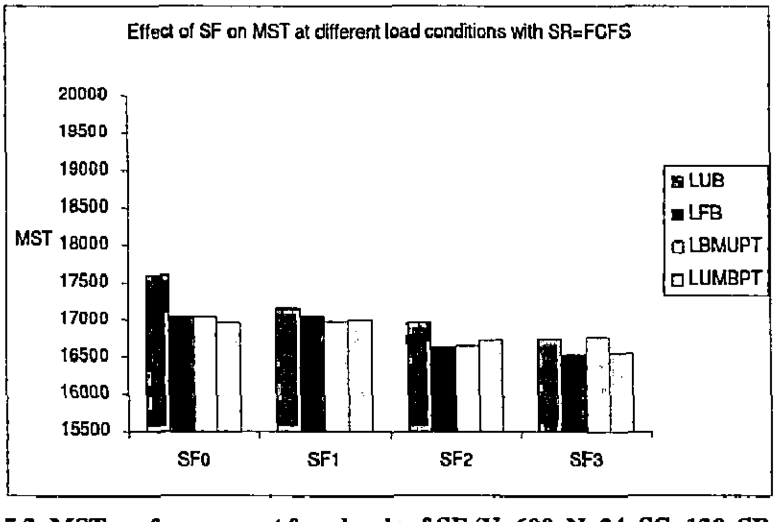


Figure 5.2: MST performance at four levels of SF (V=600, N=24, SC=120, SR=FCFS)

Table 5.1: Effect of SF on MST at different system load conditions

V=600, N=24, SC=120, SR=FCFS				
	SF0	**SF1**	**SF2**	**SF3**
LUB	17609.79	17149.99	16961.18	16734.68
LFB	17038.06	17043.15	16622.29	16530.82
LBMUPT	17054.12	16971.6	16661.07	16760
LUMBPT	16957.57	17001.96	16715.99	16534.93

Next we change the sequencing rule to SPT and perform the experiment with all other decision parameters keeping same. Figure 5.3 shows the relationship between MST and sequencing flexibility at different load conditions. It is seen from the figure that at SF0, MST is maximum for LBMUPT and minimum for LUMBPT. At SF1, again MST is maximum for LUB and minimum for LBMUPT. At SF2, MST is maximum for LUB and minimum for LUMBPT. Similarly at SF3 it is observed that MST is maximum for LBMUPT and minimum for LUMBPT. With increase in sequencing flexibility level MST decreases for all the system load conditions. The improvement in the MST is much visible in the figure with system load LBMUPT and LFB from SF0 to SF1 and SF2 to SF3 respectively.

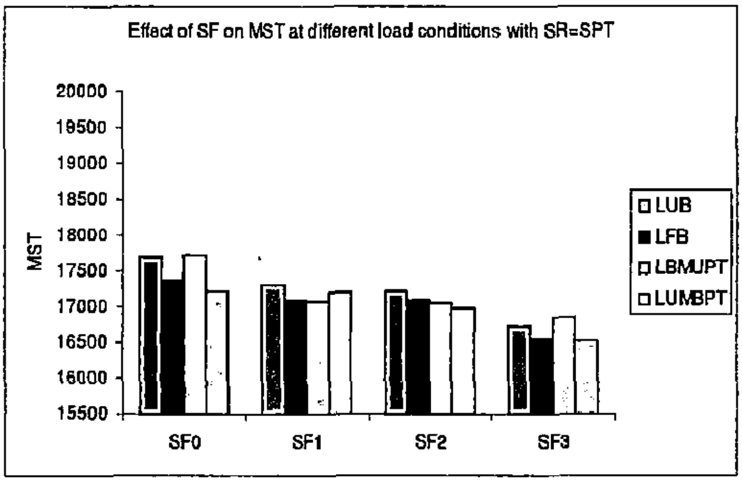


Figure 5.3: MST performance at four levels of SF (V=600, N=24, SC=120, SR=SPT)

Table 5.2: Effect of SF on MST at different system load conditions

V=600, N=24, SC=120, SR=SPT				
	SF0	SF1	SF2	SF3
LUB	17701.78	17296.56	17224.59	16709.62
LFB	17367.37	17095.47	17086.98	16542.01
LBMUPT	17727.18	17061.2	17042.23	16848.97
LUMBPT	17216	17202.41	16976.59	16526.67

Now we change the sequencing rule to HPT and observe its impact on the performance of the system. From Figure 5.3 it is seen that at SF0, MST is maximum for LUB and minimum for LUMBPT. At SF1, again MST is maximum for LUB and minimum for LUMBPT. At SF2, MST is maximum for LUB and minimum for LBMUPT. Similarly at SF3 it is observed that MST is maximum for LUB and minimum for LUMBPT. The MST is improved with the increase of sequencing flexibility at all load conditions but it is seen it has a counterproductive when the system moves from SF2 to SF3 with the load condition LBMUPT.

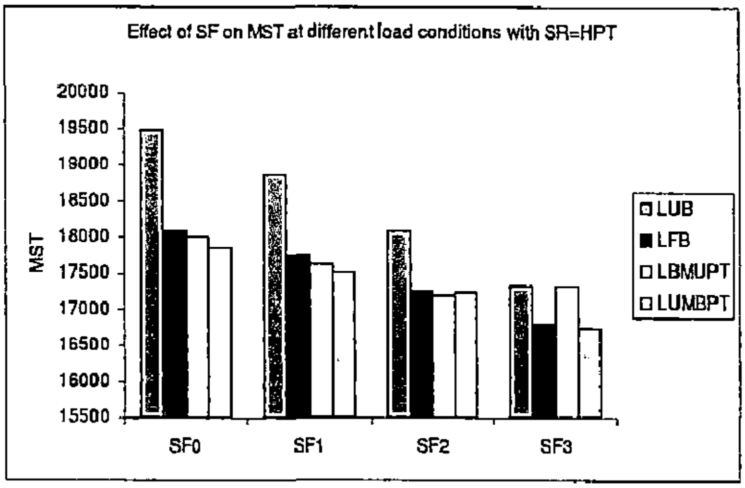


Figure 5.4: MST performance at four levels of SF (V=600, N=24, SC=120, SR=HPT)

Finally we changed the sequencing rule to LCFS and observe the performance of the system. Figure 5.5 shows the relationship between MST and sequencing flexibility for different system load conditions.

Table 5.3: MST of different load conditions with SR=HPT at 4 levels of SF

V=600, N=24, SC=120, SR=HPT				
	SF0	**SF1**	**SF2**	**SF3**
LUB	19477.89	18877.21	18092.54	17320.53
LFB	18084.99	17764.31	17269.86	16801.26
LBMUPT	17991.9	17638.6	17198.23	17327.01
LUMBPT	17839.49	17528.91	17240.88	16738.34

It is seen that at SF0, MST is maximum for LUB and minimum for LBMUPT. At SF1, again MST is maximum for LUB and minimum for LFB. At SF2, MST is maximum for LUB and minimum for LFB. Similarly at SF3 it is observed that MST is maximum for LUB and minimum for LFB. It is also seen that MST increases when system shifts from SF0 to SF1 with the load condition LBMUPT and then it improves by further increase in the level of flexibility. The system load condition LFB gives best response among all four load conditions at sequencing flexibility levels of SF1, SF2 and SF3 respectively. In all four studies carried above it is seen that with LUB system load condition MST is maximum. This is because standard deviation of processing time is highest among all load conditions.

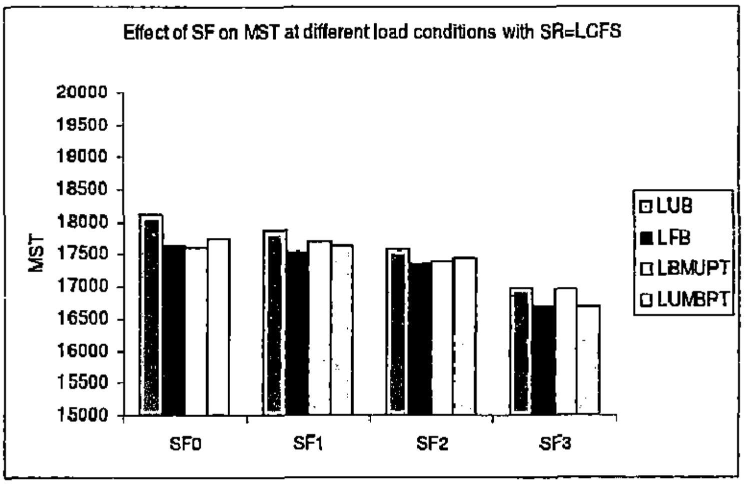


Figure 5.5: MST performance at four levels of SF (V=600, N=24, SC=120, SR=LCFS)

Table 5.4: MST of different load conditions with SR=LCFS at 4 levels of SF

V=600, N=24, SC=120, SR=LCFS				
	SF0	**SF1**	**SF2**	**SF3**
LUB	18124.17	17863.11	17576.52	16980.05
LFB	17639.96	17527.01	17347.08	16681.56
LBMUPT	17596.87	17695.9	17384.13	16952.22
LUMBPT	17742.04	17637.27	17447.54	16689.44

Table 5.5 shows the comparison of MST obtained for different sequencing rule and system load conditions. It is observed that system load conditions do affect the MST performance of SFMS for different sequencing rule and different levels of sequencing flexibility.

Table 5.5: Comparison of MST at SF and SR for different SLC

Sequencing Flexibility	Sequencing Rule	V=600, N=24, SC=120; Performance measure: MST	
		Conditions	System Load Conditions
SF0	FCFS	Maximum	LUB
		Minimum	LUMBPT
	SPT	Maximum	LBMUPT
		Minimum	LUB
	HPT	Maximum	LUB
		Minimum	LUMBPT
	LCFS	Maximum	LUB
		Minimum	LBMUPT
SF1	FCFS	Maximum	LUB
		Minimum	LBMUPT
	SPT	Maximum	LBMUPT
		Minimum	LUB
	HPT	Maximum	LUB
		Minimum	LUMBPT
	LCFS	Maximum	LUB
		Minimum	LFB
SF2	FCFS	Maximum	LUB
		Minimum	LFB
	SPT	Maximum	LUB
		Minimum	LUMBPT
	HPT	Maximum	LUB
		Minimum	LBMUPT
	LCFS	Maximum	LUB
		Minimum	LFB
SF3	FCFS	Maximum	LFB
		Minimum	LUB
	SPT	Maximum	LBMUPT
		Minimum	LUMBPT
	HPT	Maximum	LBMUPT
		Minimum	LUMBPT
	LCFS	Maximum	LUB
		Minimum	LFB

5.2.2. Effect of SF on WIP at different system load conditions

In this section we find the effect of sequencing flexibility on work-in-process (WIP) at different system load conditions. The figures 5.6 to 5.9 are drawn between WIP and sequencing flexibility at all four system load conditions. Tables 5.6 to 5.9 shows the

WIP value at four levels of sequencing flexibility under four system load conditions and four sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively.

Figure 5.6 shows the impact of sequencing flexibility under different load conditions at sequencing rule FCFS for 600 parts at a system capacity of 120 on the WIP performance of the system.

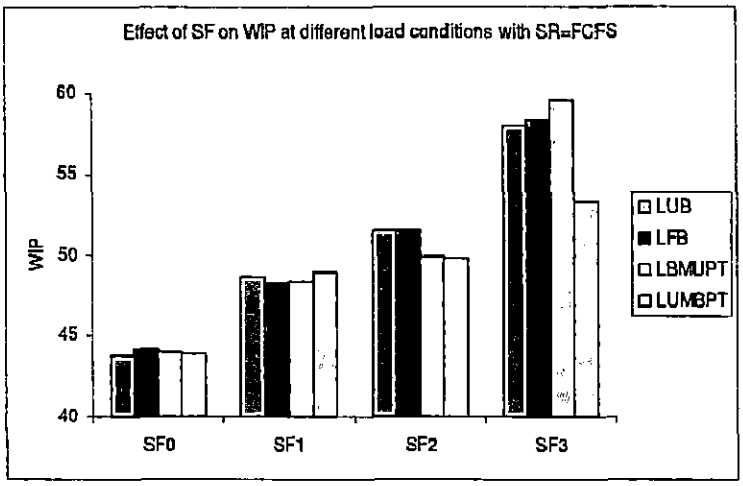


Figure 5.6: MST performance at four levels of SF (V=600, N=24, SC=120, SR=FCFS)

It is seen from the figure that at SF0, WIP is maximum for LFB and minimum for LUB. At SF1, again WIP is maximum for LUMBPT and minimum for LFB. At SF2, WIP is maximum for LFB and minimum for LUMBPT. Similarly at SF3 it is observed that WIP is maximum for LBMUPT and minimum for LUMBPT. As one adopts different levels of sequencing flexibility, WIP increases from SF0 to SF3 for almost all system load condition.

Table 5.6: WIP of different load conditions with SR=FCFS at 4 levels of SF

V=600, N=24, SC=120, SR=FCFS				
	SF0	**SF1**	**SF2**	**SF3**
LUB	43.73833	48.61067	51.4695	58.00817
LFB	44.11617	48.26033	51.519	58.22883
LBMUPT	43.95833	48.267	49.81517	59.4925
LUMBPT	43.8215	48.9225	49.73433	53.19633

Next we change the sequencing rule to SPT and perform the experiment with all other decision parameters keeping same. Figure 5.7 shows the relationship between WIP and sequencing flexibility at different load conditions. It is seen from the figure that at SF0, WIP is maximum for LUMBPT and minimum for LUB. At SF1, again WIP is maximum for LUMBPT and minimum for LFB. At SF2, WIP is maximum for LFB and minimum for LBMUPT. Similarly at SF3 it was observed that WIP is maximum for LUMBPT and minimum for LBMUPT. With increase in sequencing flexibility level WIP increases for all the system load conditions.

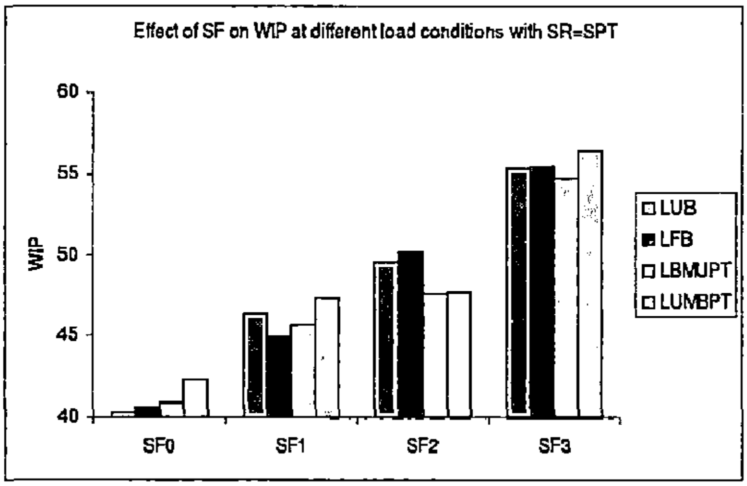


Figure 5.7: WIP performance at four levels of SF (V=600, N=24, SC=120, SR=SPT)

Table 5.7: WIP of different load conditions with SR=SPT at 4 levels of SF

V=600, N=24, SC=120, SR=SPT				
	SF0	**SF1**	**SF2**	**SF3**
LUB	40.31883	46.42083	49.54783	55.34367
LFB	40.56733	44.9195	50.14367	55.4545
LBMUPT	40.90717	45.65267	47.59433	54.796
LUMBPT	42.27433	47.343	47.70483	56.46183

Now we change the sequencing rule to HPT and observe its impact on the performance of the system. From Figure 5.8 it is seen that at SF0, WIP is maximum for LUB and minimum for LFB. At SF1, again WIP is maximum for LFB and minimum for

LUMBPT. At SF2, WIP is maximum for LBMUPT and minimum for LUMBPT. Similarly at SF3 it is observed that WIP is maximum for LBMUPT and minimum for LUMBPT. The WIP is improved with the increase of sequencing flexibility at all load conditions but it is seen it has a counter-productive when the system moves from SF2 to SF3 with the load condition LBMUPT.

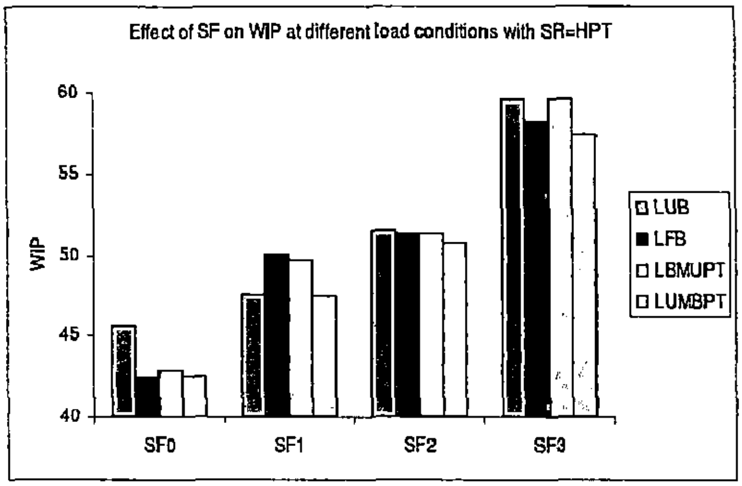


Figure 5.8: WIP performance at four levels of SF with V=600, SC=120, SL=BL, SR=HPT

Table 5.8: WIP of different load conditions with SR=HPT at 4 levels of SF

V=600, N=24, SC=120, SR=HPT				
	SF0	**SF1**	**SF2**	**SF3**
LUB	45.61867	47.48967	51.53383	59.59483
LFB	42.46067	49.929	51.3425	58.30633
LBMUPT	42.8025	49.69617	51.26	59.6205
LUMBPT	42.524	47.44667	50.73	57.41

Finally we change the sequencing rule to LCFS and observe the performance of the system. Figure 5.9 shows the relationship between WIP and sequencing flexibility for different system load conditions. It is seen that at SF0, WIP is maximum for LUMBPT and minimum for LFB. At SF1, again WIP is maximum for LBMUPT and minimum for LUB. At SF2, WIP is maximum for LUMBPT and minimum for LUB. Similarly at SF3 it is observed that WIP is maximum for LUB and minimum for LFB. It is also seen that WIP increases with the increase of sequencing flexibility level.

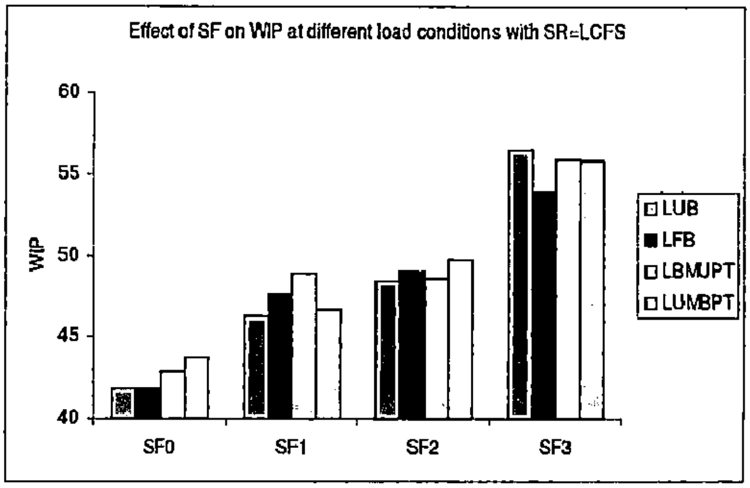


Figure 5.9: WIP performance at four levels of SF (V=600, SC=120, SL=BL, SR=LCFS)

Table 5.9: WIP of different load conditions with SR=LCFS at 4 levels of SF

V=600, N=24, SC=120, SR=LCFS				
	SF0	**SF1**	**SF2**	**SF3**
LUB	41.85533	46.31917	48.4265	56.49017
LFB	41.7925	47.63367	48.9575	53.90783
LBMUPT	42.88583	48.92283	48.61117	55.918
LUMBPT	43.7235	46.62683	49.75167	55.87717

It is clear from the above discussion that the value of WIP increases with the increase in the level of sequencing flexibility. The value of WIP indicates that the percentage of time the part is in process i.e. as much as the part is in process when it is in the system then the MST will increase. As it is discussed in the previous chapters that the part sequencing is solely depends on the dependency of the operations each over other. So that in case of SF0 all the five operation of a part performed in sequence while in SF3 these operations are fully independent and can be performed in any sequence. Hence, we conclude that there is a positive impact of sequencing flexibility on WIP performance of the system. While the system loads condition has a mix impact on the performance of the SFMS at various levels of flexibility.

Table 5.10 shows the comparison of WIP obtained for different sequencing rule and system load conditions. It is observed that system load conditions do affect the MST performance of SFMS for different sequencing rule and different levels of sequencing flexibility.

Table 5.10: Comparison of WIP at SF and SR for different SLC

Sequencing Flexibility	Sequencing Rule	V=600, N=24, SC=120; Performance measure: WIP	
		Conditions	System Load Conditions
SF0	FCFS	Maximum	LFB
		Minimum	LUB
	SPT	Maximum	LBMUPT
		Minimum	LUB
	HPT	Maximum	LUB
		Minimum	LFB
	LCFS	Maximum	LUMBPT
		Minimum	LFB
SF1	FCFS	Maximum	LUMBPT
		Minimum	LFB
	SPT	Maximum	LUMBPT
		Minimum	LFB
	HPT	Maximum	LFB
		Minimum	LUMBPT
	LCFS	Maximum	LBMUPT
		Minimum	LUB
SF2	FCFS	Maximum	LFB
		Minimum	LUMBPT
	SPT	Maximum	LFB
		Minimum	LBMUPT
	HPT	Maximum	LBMUPT
		Minimum	LUMBPT
	LCFS	Maximum	LUMBPT
		Minimum	LUB
SF3	FCFS	Maximum	LUMBPT
		Minimum	LBMUPT
	SPT	Maximum	LUMBPT
		Minimum	LBMUPT
	HPT	Maximum	LBMUPT
		Minimum	LUMBPT
	LCFS	Maximum	LUB
		Minimum	LFB

5.2.3. Effect of SF on RU at different system load conditions

In this section we find the effect of sequencing flexibility on resource utilization (RU) at different system load conditions. The figures 5.10 to 5.13 are drawn between MST and sequencing flexibility at all four system load conditions. Tables 5.11 to 5.14 shows the RU value at four levels of sequencing flexibility under four system load conditions and four sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively.

Figure 5.10 shows the impact of sequencing flexibility under different load conditions at sequencing rule FCFS for 600 parts at a system capacity of 120 on the RU performance of the system. It is seen from the figure that at SF0, RU is maximum for LUMBPT and minimum for LUB. At SF1, again RU is maximum for LUMBPT and minimum for LUB. At SF2, RU is maximum for LFB and minimum for LUB. Similarly at SF3 it is observed that RU is maximum for LFB and minimum for LUB. As one adopts different levels of sequencing flexibility, RU decreases from SF0 to SF1 for system load condition LUB and LUMBPT and then further it increases for SF2 and SF3. In other cases almost the value of RU is increases at all system load conditions with the increase of sequencing flexibility with sequencing rule FCFS.

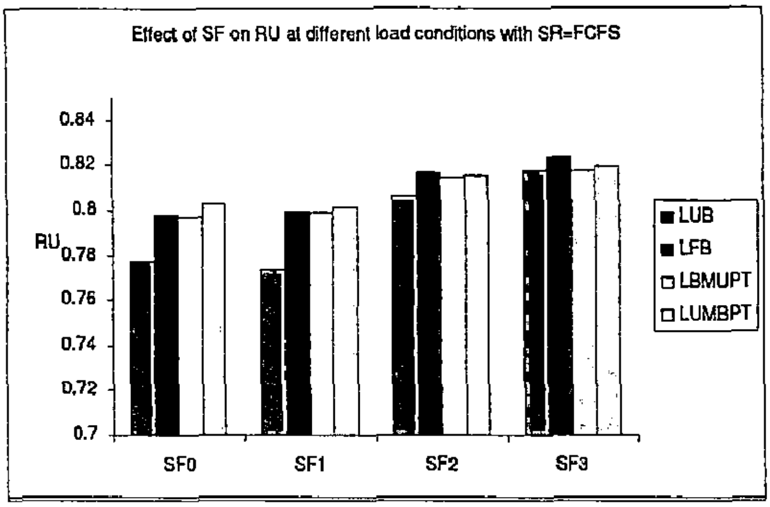


Figure 5.10: RU performance at four levels of SF (V=600, N=24, SC=120, SR=FCFS)

Table 5.11: RU of different load conditions with SR=FCFS at 4 levels of SF

V=600, N=24, SC=120, SR=FCFS				
	SF0	**SF1**	**SF2**	**SF3**
LUB	0.777528	0.773917	0.806592	0.817687
LFB	0.798028	0.799302	0.81692	0.823002
LBMUPT	0.79711	0.799468	0.814187	0.81756
LUMBPT	0.803167	0.801148	0.815493	0.819808

Next we change the sequencing rule to SPT and perform the experiment with all other decision parameters keeping same. Figure 5.11 shows the relationship between RU and sequencing flexibility at different load conditions. It is seen from the figure that at SF0, RU is maximum for LUMBPT and minimum for LBMUPT. At SF1, again RU is maximum for LUMBPT and minimum for LUB. At SF2, RU is maximum for LUMBPT and minimum for LFB. Similarly at SF3 it is observed that RU is maximum for LUMBPT and minimum for LBMUPT. With increase in sequencing flexibility level from SF0 to SF1 the value of RU decreases at system load conditions LUB while in rest of the conditions the value of RU is improved with the increase of sequencing flexibility.

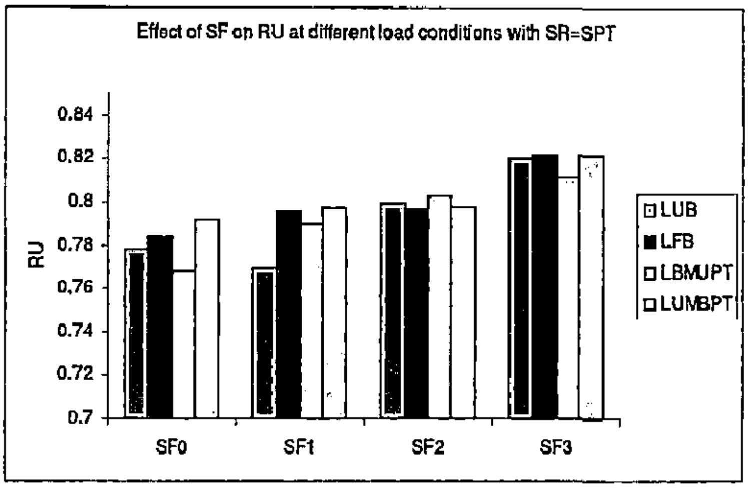


Figure 5.11: RU performance at four levels of SF (V=600, N=24, SC=120, SR=SPT)

Table 5.12: RU of different load conditions with SR=SPT at 4 levels of SF

V=600, N=24, SC=120, SR=SPT				
	SF0	**SF1**	**SF2**	**SF3**
LUB	0.77834	0.7696	0.799223	0.82002
LFB	0.783853	0.795437	0.796705	0.821588
LBMUPT	0.768188	0.790213	0.803197	0.811802
LUMBPT	0.791837	0.796767	0.797973	0.821713

Now we change the sequencing rule to HPT and observe its impact on the performance of the system. From Figure 5.12 it is seen that at SF0, RU is maximum for LUMBPT and minimum for LUB. At SF1, again RU is maximum for LBMUPT and minimum for LUB.

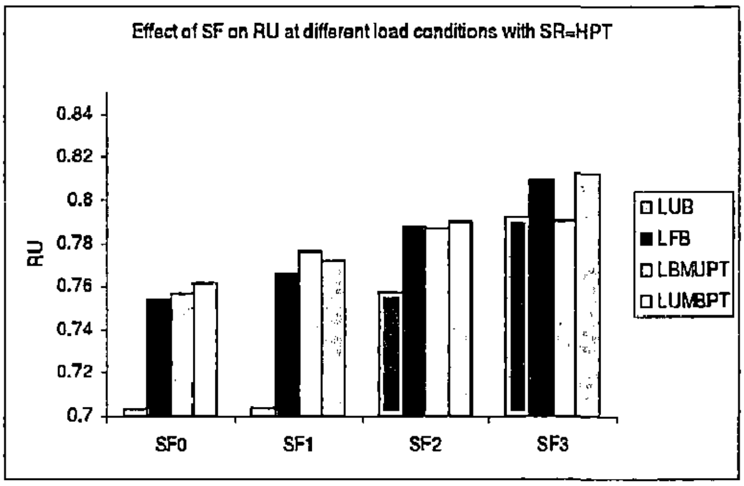


Figure 5.12: RU performance at four levels of SF (V=600, SC=120, SL=BL, SR=HPT)

At SF2, RU is maximum for LUMBPT and minimum for LUB. Similarly at SF3 it is observed that RU is maximum for LUMBPT and minimum for LBMUPT. It is seen that RU is improved with the increase of sequencing flexibility at all load conditions.

Table 5.13: RU of different load conditions with SR=HPT at 4 levels of SF

V=600, N=24, SC=120, SR=HPT				
	SF0	**SF1**	**SF2**	**SF3**
LUB	0.702873	0.703938	0.757045	0.791748
LFB	0.753288	0.765617	0.787397	0.809593
LBMUPT	0.756678	0.776087	0.787297	0.790592
LUMBPT	0.76146	0.77207	0.789783	0.812617

Finally we change the sequencing rule to LCFS and observed the performance of the system. Figure 5.13 shows the relationship between RU and sequencing flexibility for different system load conditions.

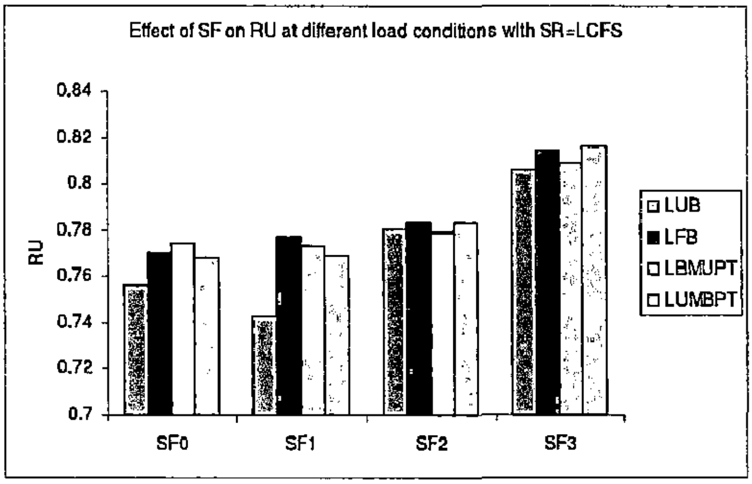


Figure 5.13: RU performance at four levels of SF (V=600, SC=120, SL=BL, SR=LCFS)

Table 5.14: RU of different load conditions with SR=LCFS at 4 levels of SF

V=600, N=24, SC=120, SR=LCFS				
	SF0	**SF1**	**SF2**	**SF3**
LUB	0.756052	0.742582	0.780727	0.806217
LFB	0.770327	0.777413	0.783472	0.814068
LBMUPT	0.774468	0.772893	0.779053	0.808827
LUMBPT	0.768152	0.769142	0.78338	0.816607

It is seen that at SF0, RU is maximum for LBMUPT and minimum for LUB. At SF1, again RU is maximum for LFB and minimum for LUB. At SF2, RU is maximum for LFB and minimum for LBMUPT. Similarly at SF3 it is observed that RU is maximum for LBMUPT and minimum for LUB. It is also seen that RU increases when system shifts from SF0 to SF1 with the load condition all system load condition except LUB while in rest of the conditions the value of RU increases with the increase of sequencing flexibility level. The improvement in the value of RU is more visible when the system changes from SF2 to SF3.

From the above discussions it is concluded that the resource utilization is higher at the higher levels of sequencing flexibility. And it also has an impact of load condition on the resource utilization. But this impact is having a mix response at all levels of flexibilities.

Table 5.15 shows the comparison of MST obtained for different sequencing rule and system load conditions. It is observed that system load conditions do affect the MST performance of SFMS for different sequencing rule and different levels of sequencing flexibility.

Table 5.15: Comparison of RU at SF and SR for different SLC

Sequencing Flexibility	Sequencing Rule	V=600, N=24, SC=120; Performance measure: RU	
		Conditions	System Load Conditions
SF0	FCFS	Maximum	LUMBPT
		Minimum	LUB
	SPT	Maximum	LUMBPT
		Minimum	LBMUPT
	HPT	Maximum	LUMBPT
		Minimum	LUB
	LCFS	Maximum	LBMUPT
		Minimum	LUB
SF1	FCFS	Maximum	LUMBPT
		Minimum	LUB
	SPT	Maximum	LUMBPT
		Minimum	LUM
	HPT	Maximum	LBMUPT
		Minimum	LUB
	LCFS	Maximum	LFB
		Minimum	LUB
SF2	FCFS	Maximum	LFB
		Minimum	LUB
	SPT	Maximum	LUMBPT
		Minimum	LFB
	HPT	Maximum	LUMBPT
		Minimum	LUB
	LCFS	Maximum	LFB
		Minimum	LBMUPT
SF3	FCFS	Maximum	LFB
		Minimum	LUB
	SPT	Maximum	LUMBPT
		Minimum	LBMUPT
	HPT	Maximum	LUMBPT
		Minimum	LBMUPT
	LCFS	Maximum	LBMUPT
		Minimum	LUB

5.2.4. Effect of SF on MST at different sequencing rules

In this section we find the effect of sequencing flexibility on make-span time (MST) at different sequencing rules. The figures 5.14 to 5.17 are drawn between MST and sequencing flexibility at all four sequencing rules. Tables 5.16 to 5.19 shows the

MST value at four levels of sequencing flexibility under four sequencing rules i.e. FCFS, SPT, HPT and LCFS and four system load conditions i.e. LUB, LFB, LBMUPT and LUMBPT respectively.

Figure 5.14 shows the impact of sequencing flexibility under sequencing rules at system load condition LUB for 600 parts at a system capacity of 120 on the MST performance of the system. It is seen from the figure that at SF0, MST is maximum for HPT and minimum for FCFS. At SF1, again MST is maximum for HPT and minimum for FCFS. At SF2, MST is maximum for HPT and minimum for FCFS. Similarly at SF3 it was observed that MST is maximum for HPT and minimum for SPT. As one adopts different levels of sequencing flexibility, MST decreases from SF0 to SF3 for all sequencing rules except SPT. In SPT, MST decreases from SF0 to SF1 but from SF1 to SF2 there is a slight increase in the MST and then further decreases with the increase of sequencing flexibility. One interesting observation we make from Figure 5.14 was that as one moves from SF0 to SFI there is decrease in MST with HPT, FCFS and LCFS sequencing rules and with SPT rule there is mix impact on MST when LUB load condition is used.

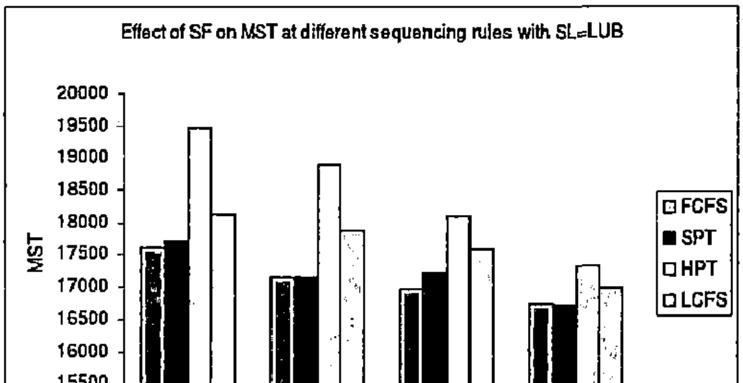


Figure 5.14: MST performance at four levels of SF (V=600, N=24, SC=120, SL=LUB)

Table 5.16: MST of different sequencing rules with SL=LUB at 4 levels of SF

V=600, N=24, SC=120, SL=LUB				
	SF0	SF1	SF2	SF3
FCFS	17609.79	17138.78	16961.18	16734.68
SPT	17701.78	17149.99	17224.59	16709.62
HPT	19477.89	18877.21	18092.54	17320.53
LCFS	18124.17	17863.11	17576.52	16980.05

Next we change the system load to LFB and perform the experiment with all other decision parameters keeping same. Figure 5.15 shows the relationship between MST and sequencing flexibility at different sequencing rules. It is seen from the figure that at SF0, MST is maximum for HPT and minimum for FCFS. At SF1, again MST is maximum for HPT and minimum for FCFS. At SF2, MST is maximum for LCFS and minimum for FCFS. Similarly at SF3 it is observed that MST is maximum for HPT and minimum for FCFS. With increase in sequencing flexibility level MST decreases for all the sequencing rules. The improvement in the MST is much visible in the figure with sequencing rule FCFS from SF1 to SF2.

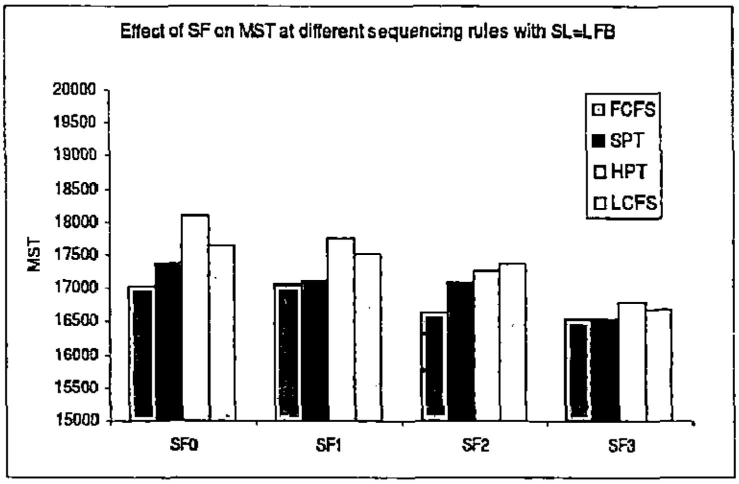


Figure 5.15: MST performance at four levels of SF (V=600, N=24, SC=120, SL=LFB)

Table 5.17: MST of different sequencing rules with SL=LFB at 4 levels of SF

V=600, N=24, SC=120, SL=LFB				
	SF0	SF1	SF2	SF3
FCFS	17038.06	17043.15	16622.29	16530.82
SPT	17367.37	17095.47	17086.98	16542.01
HPT	18084.99	17764.31	17269.86	16801.26
LCFS	17639.96	17527.01	17347.08	16681.56

Now we change the system load to LBMUPT and observe its impact on the performance of the system. From Figure 5.16 it is seen that at SF0, MST is maximum for HPT and minimum for FCFS. At SF1, again MST is maximum for LCFS and minimum for FCFS. At SF2, MST is maximum for LCFS and minimum for FCFS. Similarly at SF3 it is observed that MST is maximum for HPT and minimum for FCFS. The MST is improved with the increase of sequencing flexibility at all sequencing rules but it is seen it has a counter-productive when the system moves from SF2 to SF3 with the sequencing rules HPT and FCFS.

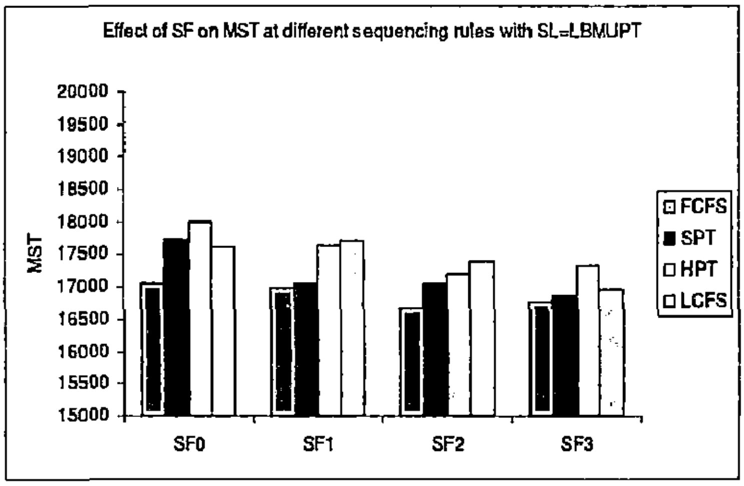


Figure 5.16: MST performance at four levels of SF (V=600, N=24, SC=120, SL= LBMUPT)

Table 5.18: MST of different sequencing rules with SL= LBMUPT at 4 levels of SF

V=600, N=24, SC=120, SL=LBMUPT				
	SF0	SF1	SF2	SF3
FCFS	17054.12	16971.6	16661.07	16760
SPT	17727.18	17061.2	17042.23	16848.97
HPT	17991.9	17638.6	17198.23	17327.01
LCFS	17596.87	17695.9	17384.13	16952.22

Finally we change the system load to LUMBPT and observe the performance of the system. Figure 5.17 shows the relationship between MST and sequencing flexibility for different sequencing rules.

It is seen that at SF0, MST is maximum for HPT and minimum for FCFS. At SF1, again MST is maximum for LCFS and minimum for FCFS. At SF2, MST is maximum for LCFS and minimum for FCFS. Similarly at SF3 it is observed that MST is maximum for HPT and minimum for SPT. It is also seen that MST increases when system shifts from SF0 to SF1 with the sequencing rule FCFS and then it improves by further increase in the level of flexibility. The sequencing rule FCFS gives best performance in most of the condition at levels of sequencing flexibility except at SF3.

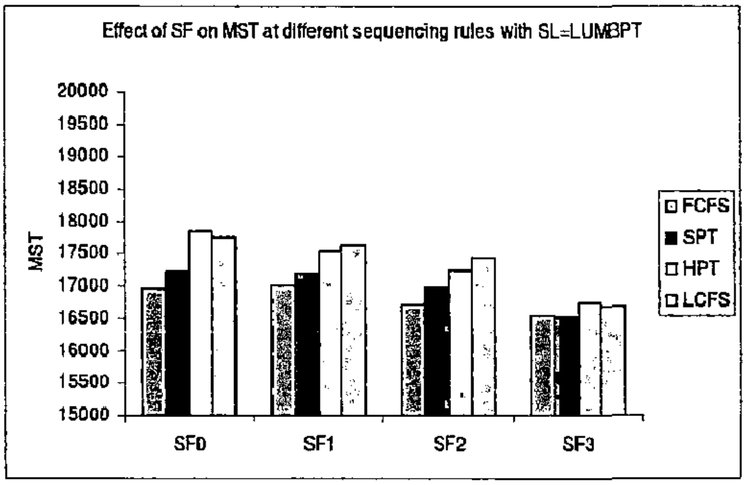


Figure 5.17: MST performance at four levels of SF with V=600, N=24, SC=120, SL=LUMBPT

Table 5.19: MST of different sequencing rules with SL= LUMBPT at 4 levels of SF

V=600, N=24, SC=120, SL=LUMBPT				
	SF0	**SF1**	**SF2**	**SF3**
FCFS	16957.57	17001.96	16715.99	16534.93
SPT	17216	17202.41	16976.59	16526.67
HPT	17839.49	17528.91	17240.88	16738.34
LCFS	17742.04	17637.27	17447.54	16689.44

From the above discussion it is found that the makespan is decreases with the increase of sequencing flexibility level. It is also found that the sequencing rule FCFS has the best performance among the four sequencing rule. As well this variation is very much visible at lower level of sequencing flexibility in comparison to the higher level. This variation in the MST is present because, at lower level of sequencing flexibility the formation of queue is more likely in comparison to the higher level of sequencing flexibility.

Table 5.20: Comparison of MST at SF and SR for different SLC

Sequencing Flexibility	System load condition	V=600, N=24, SC=120; Performance measure: MST	
		Conditions	Sequencing rule
SF0	LUB	Maximum	HPT
		Minimum	FCFS
	LFB	Maximum	HPT
		Minimum	FCFS
	LBMUPT	Maximum	HPT
		Minimum	FCFS
	LUMBPT	Maximum	HPT
		Minimum	FCFS
SF1	LUB	Maximum	HPT
		Minimum	FCFS
	LFB	Maximum	HPT
		Minimum	FCFS
	LBMUPT	Maximum	LCFS
		Minimum	FCFS
	LUMBPT	Maximum	LCFS
		Minimum	FCFS
SF2	LUB	Maximum	HPT
		Minimum	FCFS
	LFB	Maximum	LCFS
		Minimum	FCFS
	LBMUPT	Maximum	LCFS
		Minimum	FCFS
	LUMBPT	Maximum	LCFS
		Minimum	FCFS
SF3	LUB	Maximum	HPT
		Minimum	SPT
	LFB	Maximum	HPT
		Minimum	FCFS
	LBMUPT	Maximum	HPT
		Minimum	FCFS
	LUMBPT	Maximum	HPT
		Minimum	SPT

Table 5.20 shows the comparison of MST obtained for different sequencing rule and system load conditions. It is observed that system load conditions do affect the MST performance of SFMS for different sequencing rule and different levels of sequencing flexibility.

5.2.5. Effect of SF on WIP at different sequencing rules

In this section we find the effect of sequencing flexibility on work-in-process (WIP) at different sequencing rules. The figures 5.18 to 5.21 are drawn between WIP and sequencing flexibility at all four sequencing rules. Tables 5.21 to 5.24 shows the WIP value at four levels of sequencing flexibility under four sequencing rules i.e. FCFS, SPT, HPT and LCFS and four system load conditions i.e. LUB, LFB, LBMUPT and LUMBPT respectively.

Figure 5.18 shows the impact of sequencing flexibility under different sequencing rules at system load LUB for 600 parts at a system capacity of 120 on the WIP performance of the system. It is seen from the figure that at SF0, WIP is maximum for HPT and minimum for SPT. At SF1, again WIP is maximum for FCFS and minimum for LCFS. At SF2, WIP is maximum for HPT and minimum for LCFS. Similarly at SF3 it is observed that WIP is maximum for HPT and minimum for SPT. As one adopts different levels of sequencing flexibility, WIP increases from SF0 to SF3 for almost all system load condition.

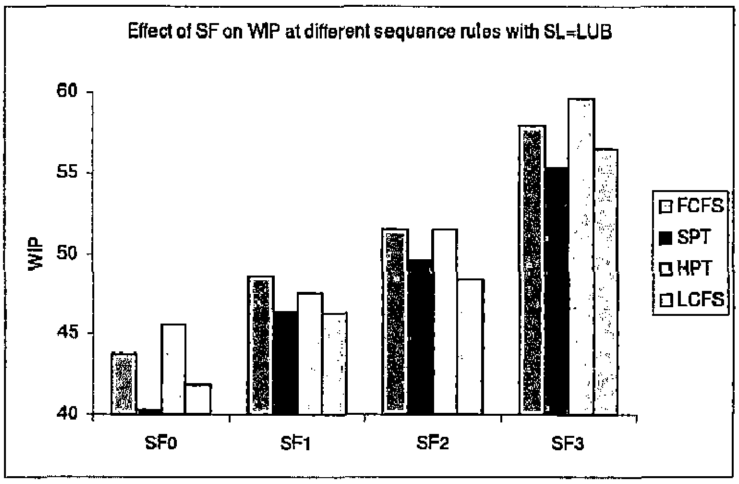


Figure 5.18: WIP performance at four levels of SF (V=600, N=24, SC=120, SL= LUB)

Table 5.21: WIP of different sequencing rules with SL= LUB at 4 levels of SF

V=600, N=24, SC=120, SL=LUB				
	SF0	**SF1**	**SF2**	**SF3**
FCFS	43.73833	48.61067	51.4695	58.00817
SPT	40.31883	46.42083	49.54783	55.34367
HPT	45.61867	47.48967	51.53383	59.59483
LCFS	41.85533	46.31917	48.4265	56.49017

Next we change the system load to LFB and perform the experiment with all other decision parameters keeping same. Figure 5.19 shows the relationship between WIP and sequencing flexibility at different sequencing rules. It is seen from the figure that at SF0, WIP is maximum for FCFS and minimum for SPT. At SF1, again WIP is maximum for HPT and minimum for SPT. At SF2, WIP is maximum for FCFS and minimum for LCFS. Similarly at SF3 it is observed that WIP is maximum for HPT and minimum for LCFS. With increase in sequencing flexibility level WIP increases for all the system load conditions.

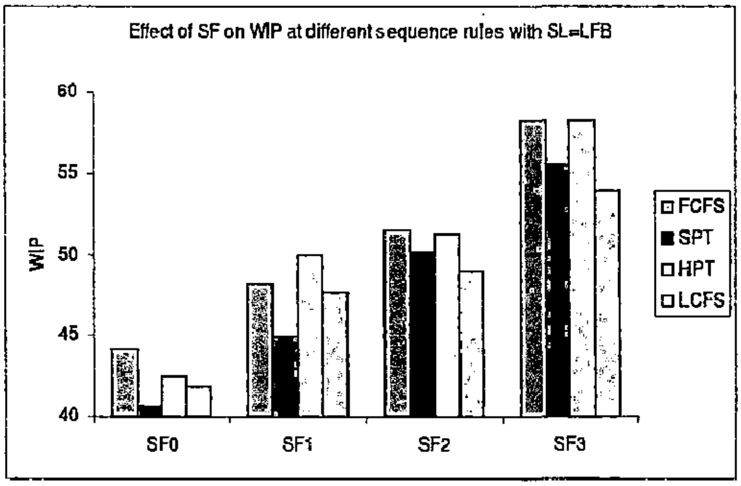


Figure 5.19: MST performance at four levels of SF with V=600, N=24, SC=120, SL= LFB

Table 5.22: WIP of different sequencing rules with SL= LFB at 4 levels of SF

V=600, N=24, SC=120, SL=LFB				
	SF0	**SF1**	**SF2**	**SF3**
FCFS	44.11617	48.26033	51.519	58.22883
SPT	40.56733	44.9195	50.14367	55.4545
HPT	42.46067	49.929	51.3425	58.30633
LCFS	41.7925	47.63367	48.9575	53.90783

Now we change the system load to LBMUPT and observe its impact on the performance of the system. From Figure 5.20 it is seen that at SF0, WIP is maximum for FCFS and minimum for SPT. At SF1, again WIP is maximum for HPT and minimum for SPT. At SF2, WIP is maximum for HPT and minimum for SPT. Similarly at SF3 it is observed that WIP is maximum for HPT and minimum for SPT. The WIP is increased with the increase of sequencing flexibility at all load conditions but it is seen the increase is more visible when the system moves from SF2 to SF3 at all sequencing rule.

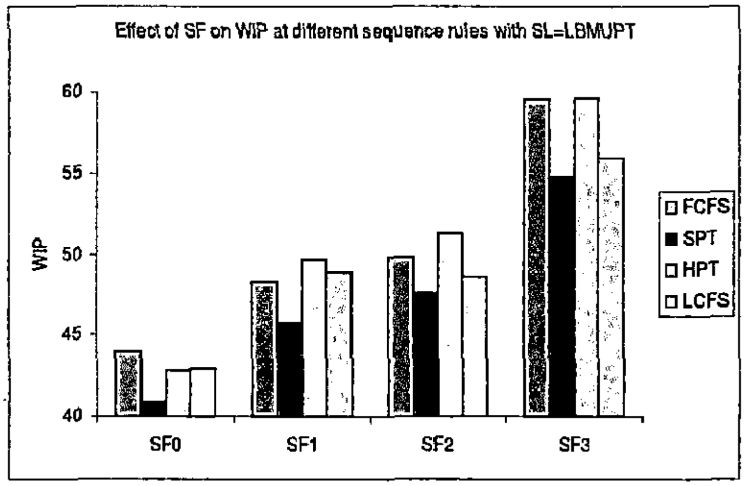


Figure 5.20: WIP performance at four levels of SF with V=600, N=24, SC=120, SL= LBMUPT

Table 5.23: WIP of different sequencing rules with SL= LBMUPT at 4 levels of SF

V=600, N=24, SC=120, SL=LBMUPT				
	SF0	**SF1**	**SF2**	**SF3**
FCFS	43.95833	48.267	49.81517	59.4925
SPT	40.90717	45.65267	47.59433	54.796
HPT	42.8025	49.69617	51.26	59.6205
LCFS	42.88583	48.92283	48.61117	55.918

Finally we changed the system load to LUMBPT and observe the performance of the system. Figure 5.21 shows the relationship between WIP and sequencing flexibility for different sequencing rules. It is seen that at SF0, WIP is maximum for FCFS and minimum for SPT. At SF1, again WIP is maximum for FCFS and minimum for LCFS. At SF2, WIP is maximum for HPT and minimum for SPT. Similarly at SF3 it is observed that WIP is maximum for HPT and minimum for FCFS. It is seen from the figure that the WIP increase with the increase of sequencing flexibility with all sequencing rules.

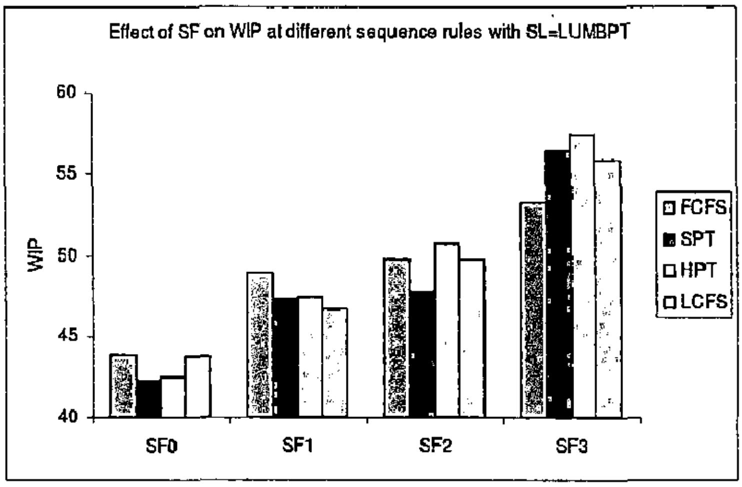


Figure 5.21: WIP performance at four levels of SF with V=600, N=24, SC=120, SL=LUMBPT

Table 5.24: WIP of different sequencing rules with SL= LUMBPT at 4 levels of SF

V=600, N=24, SC=120, SL=LUMBPT				
	SF0	**SF1**	**SF2**	**SF3**
FCFS	43.8215	48.9225	49.73433	53.19633
SPT	42.27433	47.343	47.70483	56.46183
HPT	42.524	47.44667	50.7205	57.41467
LCFS	43.7235	46.62683	49.75167	55.87717

It is clear from the above discussion that the value of WIP is increased with the increase in the level of sequencing flexibility. Hence, we conclude that there is a positive effect of sequencing flexibility on the WIP irrespective of the sequencing rules.

Table 5.25: Comparison of WIP at SF and SR for different SLC

Sequencing Flexibility	System load condition	V=600, N=24, SC=120; Performance measure: WIP	
		Conditions	Sequencing rule
SF0	LUB	Maximum	HPT
		Minimum	SPT
	LFB	Maximum	FCFS
		Minimum	SPT
	LBMUPT	Maximum	FCFS
		Minimum	SPT
	LUMBPT	Maximum	FCFS
		Minimum	SPT
SF1	LUB	Maximum	FCFS
		Minimum	LCFS
	LFB	Maximum	HPT
		Minimum	SPT
	LBMUPT	Maximum	HPT
		Minimum	SPT
	LUMBPT	Maximum	FCFS
		Minimum	LCFS
SF2	LUB	Maximum	HPT
		Minimum	LCFS
	LFB	Maximum	FCFS
		Minimum	LCFS
	LBMUPT	Maximum	HPT
		Minimum	SPT
	LUMBPT	Maximum	HPT
		Minimum	SPT
SF3	LUB	Maximum	HPT
		Minimum	SPT
	LFB	Maximum	HPT
		Minimum	LCFS
	LBMUPT	Maximum	HPT
		Minimum	SPT
	LUMBPT	Maximum	HPT
		Minimum	FCFS

Table 5.25 shows the comparison of MST obtained for different sequencing rule and system load conditions. It is observed that system load conditions do affect the MST performance of SFMS for different sequencing rule and different levels of sequencing flexibility.

5.2.6. Effect of SF on RU at different sequencing rules

In this section we find the effect of sequencing flexibility on resource utilization (RU) at different sequencing rules. The figures 5.22 to 5.25 are drawn between RU and sequencing flexibility at all four sequencing rules. Tables 5.26 to 5.29 shows the RU value at four levels of sequencing flexibility under four sequencing rules i.e. FCFS, SPT, HPT and LCFS and four system load conditions i.e. LUB, LFB, LBMUPT and LUMBPT respectively.

Figure 5.22 shows the impact of sequencing flexibility under different sequencing rules at system load LUB for 600 parts at a system capacity of 120 on the RU performance of the system. It is seen from the figure that at SF0, RU is maximum for SPT and minimum for HPT. At SF1, again RU is maximum for FCFS and minimum for HPT. At SF2, RU is maximum for FCFS and minimum for HPT. Similarly at SF3 it is observed that RU is maximum for SPT and minimum for HPT. As one adopts different levels of sequencing flexibility, RU decreases from SF0 to SF1 for all sequencing rules except HPT and then further it increases for SF2 and SF3.

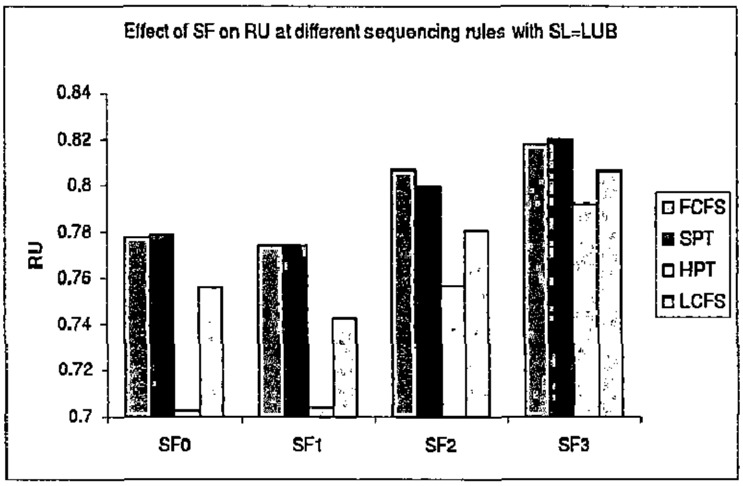


Figure 5.22: RU performance at four levels of SF with V=600, N=24, SC=120, SL= LUB

Table 5.26: RU of different sequencing rules with SL= LUB at 4 levels of SF

V=600, N=24, SC=120, SL=LUB				
	SF0	SF1	SF2	SF3
FCFS	0.777528	0.774826	0.806592	0.817687
SPT	0.77834	0.773917	0.799223	0.82002
HPT	0.702873	0.703938	0.757045	0.791748
LCFS	0.756052	0.742582	0.780727	0.806217

Next we change the system load to LFB and perform the experiment with all other decision parameters keeping same. Figure 5.23 shows the relationship between RU and sequencing flexibility at different sequencing rules. It is seen from the figure that at SF0, RU is maximum for FCFS and minimum for HPT. At SF1, again RU was maximum for FCFS and minimum for HPT. At SF2, RU was maximum for FCFS and minimum for LCFS. Similarly at SF3 it was observed that RU is maximum for FCFS and minimum for HPT. With increase in sequencing flexibility level the value of RU increases at all sequencing rules. This variation is more visible at lower level of sequencing flexibility in comparison to the higher level of sequencing flexibility.

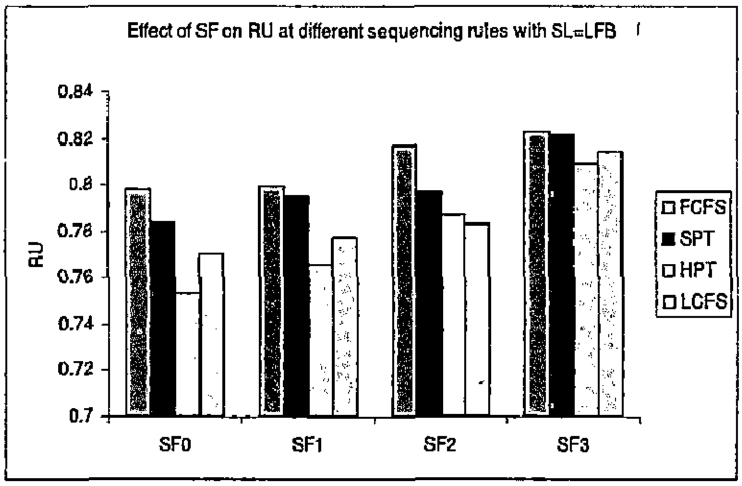


Figure 5.23: RU performance at four levels of SF with V=600, N=24, SC=120, SL= LFB

Table 5.27: RU of different sequencing rules with SL= LFB at 4 levels of SF

V=600, N=24, SC=120, SL=LFB				
	SF0	**SF1**	**SF2**	**SF3**
FCFS	0.798028	0.799302	0.81692	0.823002
SPT	0.783853	0.795437	0.796705	0.821588
HPT	0.753288	0.765617	0.787397	0.809593
LCFS	0.770327	0.777413	0.783472	0.814068

Now we change the system load to LBMUPT and observe its impact on the performance of the system. From Figure 5.24 it is seen that at SF0, RU is maximum for FCFS and minimum for HPT. At SF1, again RU is maximum for FCFS and minimum for LCFS. At SF2, RU was maximum for FCFS and minimum for LCFS. Similarly at SF3 it was observed that RU is maximum for FCFS and minimum for HPT. The RU was improved with the increase of sequencing flexibility at all sequencing rules

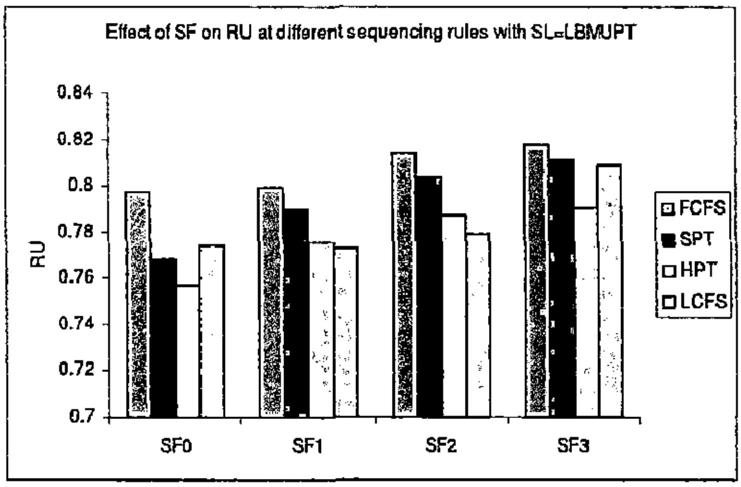


Figure 5.24: RU performance at four levels of SF with V=600, N=24, SC=120, SL=LBMUPT

Table 5.28: RU of different sequencing rules with SL= LBMUPT at 4 levels of SF

V=600, N=24, SC=120, SL=LBMUPT				
	SF0	**SF1**	**SF2**	**SF3**
FCFS	0.79711	0.799468	0.814187	0.81756
SPT	0.768188	0.790213	0.803197	0.811802
HPT	0.756678	0.776087	0.787297	0.790592
LCFS	0.774468	0.772893	0.779053	0.808827

Finally we change the system load to LUMBPT and observe the performance of the system. Figure 5.25 shows the relationship between RU and sequencing flexibility for different sequencing rules. It was seen that at SF0, RU is maximum for FCFS and minimum for HPT. At SF1, again RU is maximum for FCFS and minimum for LCFS. At SF2, RU was maximum for FCFS and minimum for LCFS. Similarly at SF3 it was observed that RU is maximum for SPT and minimum for HPT. It was also seen that RU increases with the increase of sequencing flexibility. The effect of sequencing rules are more visible at lower level of sequencing flexibility while at SF3 the impact of sequencing rules are very insignificant.

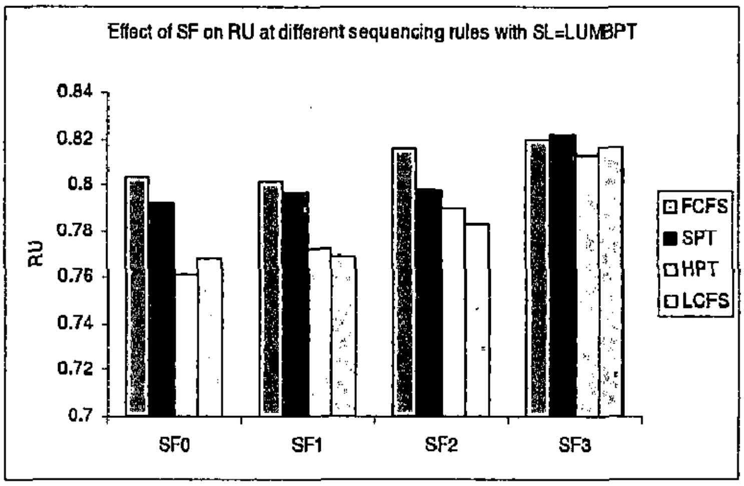


Figure 5.25: RU performance at four levels of SF (V=600, N=24, SC=120, SL=LUMBPT)

Table 5.29: RU of different sequencing rules with SL= LUMBPT at 4 levels of SF

V=600, N=24, SC=120, SL=LUMBPT				
	SF0	**SF1**	**SF2**	**SF3**
FCFS	0.803167	0.801148	0.815493	0.819808
SPT	0.791837	0.796767	0.797973	0.821713
HPT	0.76146	0.77207	0.789783	0.812617
LCFS	0.768152	0.769142	0.78338	0.816607

From the above discussions it is concluded that the resource utilization is higher at the higher levels of sequencing flexibility. And it also has an impact of sequencing rules on the resource utilization. But this impact is having a mix response at all levels of sequencing flexibilities.

Table 5.30: Comparison of RU at SF and SR for different SLC

Sequencing Flexibility	System load condition	V=600, N=24, SC=120; Performance measure: RU	
		Conditions	Sequencing rule
SF0	LUB	Maximum	SPT
		Minimum	HPT
	LFB	Maximum	FCFS
		Minimum	HPT
	LBMUPT	Maximum	FCFS
		Minimum	HPT
	LUMBPT	Maximum	FCFS
		Minimum	HPT
SF1	LUB	Maximum	FCFS
		Minimum	HPT
	LFB	Maximum	FCFS
		Minimum	HPT
	LBMUPT	Maximum	FCFS
		Minimum	LCFS
	LUMBPT	Maximum	FCFS
		Minimum	LCFS
SF2	LUB	Maximum	FCFS
		Minimum	HPT
	LFB	Maximum	FCFS
		Minimum	LCFS
	LBMUPT	Maximum	FCFS
		Minimum	LCFS
	LUMBPT	Maximum	FCFS
		Minimum	LCFS
SF3	LUB	Maximum	SPT
		Minimum	HPT
	LFB	Maximum	FCFS
		Minimum	HPT
	LBMUPT	Maximum	FCFS
		Minimum	HPT
	LUMBPT	Maximum	SPT
		Minimum	HPT

Table 5.25 shows the comparison of RU obtained for different sequencing rule and system load conditions. It is observed that system load conditions do affect the MST performance of SFMS for different sequencing rule and different levels of sequencing flexibility.

5.3 Conclusion

In this chapter, the simulation experiments are carried out with four load conditions (i.e. LUB, LFB, LBMUPT, and LUMBPT) and four sequencing rules (i.e. FCFS, SPT, HPT, and LCFS) at four levels of sequencing flexibility. The performance of the system is measured by three parameters like makespan, work-in-process and resource utilization. In the result it is found that the performance improves with the increase of sequencing flexibility in most of the combinations. It is concluded from the above results that the load condition has an impact on all the performance measures. The LFB is found the best among the four selected load conditions. Further, it is concluded that the sequencing rules at the queue also has some impact on the performance of the system. It is found that this impact is more at lower level of sequencing flexibility because the formation of queue is more likely at lower level of sequencing flexibility. Hence, from the above discussion the sequencing rule FCFS has the best performance among the four selected sequencing rules.

Performance of SFMS under Routing Flexibility

6.1 Introduction

In Chapter 5, we performed a series of experiments for studying the effect of sequencing flexibility under different decision scenarios. The implementation of sequencing flexibility was done in the first phase of SFMS. In this chapter we develop the second phase of the system in which the design decisions considered is routing flexibility and system capacity (buffer size), planning decisions include different system load conditions and system configurations and control decisions include dispatching and sequencing rules. In this chapter three important decisions i.e. decisions related are design, planning and control are considered for experimentation. Design decisions considered are four routing flexibility levels (RF0, RF1, RF2 and RF3) and system capacity level is kept at 120 (buffer size = 20). Planning decision include four system load conditions (load fully unbalanced (LUB), load fully balanced (LFB), load balanced on machine and unbalanced processing time (LBMUPT) and load unbalance on machine and balanced processing time (LUMBPT). Control decisions include four sequencing rules (FCFS, SPT, HPT and LCFS) and one dispatching rule (MINQ). The performance of the system is evaluated using performance measures such as make-span time (MST), work-in-process (WIP), and average resource utilization (RU). The stochastic environment was developed by providing normal distribution for processing time, and exponential distribution for inter-arrival time of parts in the system. The processing time and their respective mean and standard deviation are given Appendix A (Table A1 to

A4). The sequence of operations for all the parts operating under different load conditions and routing flexibility levels are shown in the Appendix 'C' (Table C1 to C4).

Simulation model for SFMS is developed in Arena simulation software. The developed models are used to conduct a series of experiments to investigate the effects of routing flexibility, system capacity, system load conditions and part sequencing rules. In SFMS the simulation experimentation first involves determining the study data set. For this a number of experimental sets were performed with different number of replications in each set as discussed in the chapter 5. So in view of this observation it was decided to take 15 replications for each set of experiment. The average of the results obtained from 15 replications is used for analysis purpose.

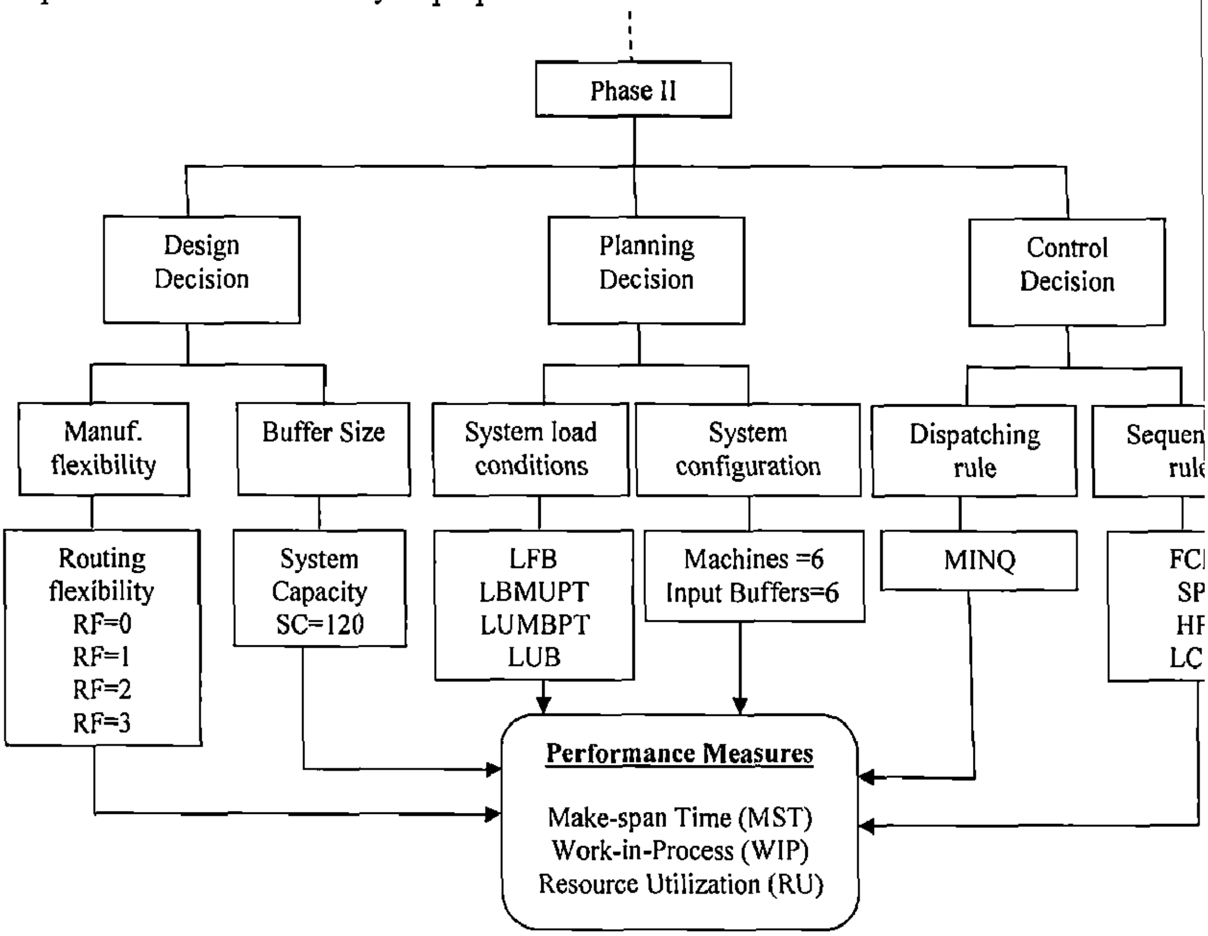


Figure 6.0: Salient Features of the Study of Phase II

6.2 Simulation results under routing flexibility

As stated earlier SFMS is developed under phased manner. In the first phase we considered sequencing flexibility as design decision. Here in the second phase we consider the routing flexibility as design decision. The effect of routing flexibility on the performance of SFMS is evaluated as given in the figure 6.0.

6.2.1. Effect of RF on MST at different system load conditions

In this section we find the effect of routing flexibility on MST at different system load conditions. The figures 6.1 to 6.4 are drawn between MST and routing flexibility at all four system load conditions. Tables 6.1 to 6.4 shows the MST value at four levels of routing flexibility under four system load conditions and four sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively.

Figure 6.1 shows the impact of routing flexibility under different load conditions at sequencing rule FCFS for 600 parts at a system capacity of 120 on the MST performance of the system. It is seen from the figure that at RF0, MST is maximum for LUB and minimum for LUMBPT. At RF1, again MST is maximum for LUB and minimum for LBMUPT. At RF2, MST is maximum for LUB and minimum for LFB. Similarly at RF3 it is observed that MST is maximum for LUB and minimum for LFB. As one adopts different levels of routing flexibility, MST decreases from RF0 to RF3 for all system load condition. But this improvement is more significant when the system shifts from RF0 to RF1. By further increase in the routing flexibility does not have any significant effect the performance of the system.

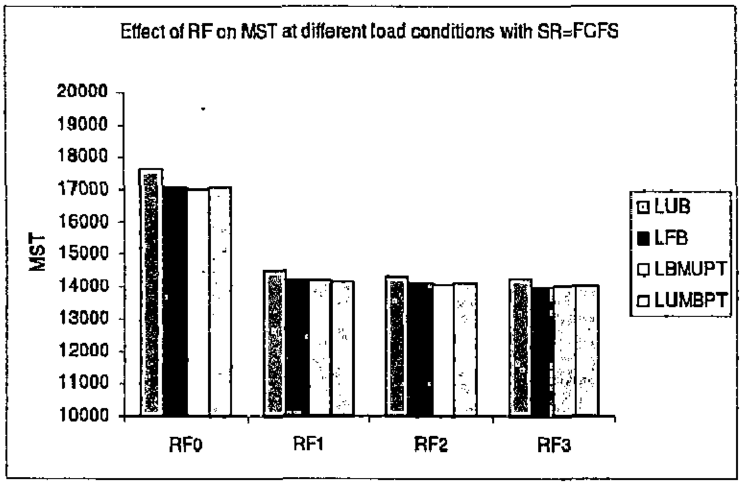


Figure 6.1: MST performance at four levels of RF (V=600, N=24, SC=120, SR=FCFS)

Table 6.1: MST of different load conditions with SR=FCFS at 4 levels of RF

V=600, N=24, SC=120, SL=FCFS				
	RF0	**RF1**	**RF2**	**RF3**
LUB	17609.79	14480.1	14320.61	14270.25
LFB	17038.06	14201.38	14103.08	13963.16
LUMBPT	16985.09	14208.57	14046.53	14016
LBMUPT	17054.12	14177.62	14091.17	14010.95

Next we change the sequencing rule to SPT and perform the experiment with all other decision parameters keeping same. Figure 6.2 shows the relationship between MST and routing flexibility at different load conditions. It is seen from the figure that at RF0, MST is maximum for LUMBPT and minimum for LBMUPT. At RF1, again MST is maximum for LUB and minimum for LBMUPT. At RF2, MST is maximum for LUB and minimum for LUMBPT. Similarly at RF3 it is observed that MST is maximum for LUB and minimum for LUMBPT. With increase in routing flexibility level MST decreases for all the system load conditions. The improvement in the MST is much significant when the system shifts from RF0 to RF1.

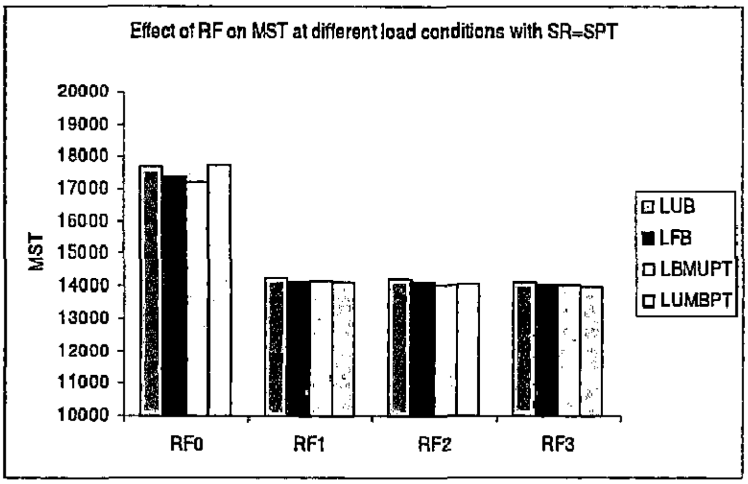


Figure 6.2: MST performance at four levels of RF (V=600, N=24, SC=120, SR=SPT)

Table 6.2: MST of different load conditions with SR=SPT at 4 levels of RF

V=600, N=24, SC=120, SL=SPT				
	RF0	**RF1**	**RF2**	**RF3**
LUB	17701.78	14244.43	14207.43	14120.99
LFB	17367.37	14129.01	14105.43	13989.24
LUMBPT	17216	14142.75	14018.37	13993.91
LBMUPT	17727.18	14118.76	14037.58	13971.13

Now we change the sequencing rule to HPT and observe its impact on the performance of the system. From Figure 6.2 it is seen that at RF0, MST is maximum for LUB and minimum for LUMBPT. At RF1, again MST is maximum for LUB and minimum for LUMBPT. At RF2, MST is maximum for LUB and minimum for LBMUPT. Similarly at RF3 it is observed that MST is maximum for LUB and minimum for LUMBPT. The MST is improved with the increase of routing flexibility at all load conditions but it is seen that this improvement is more visible at the initial levels of the routing flexibility.

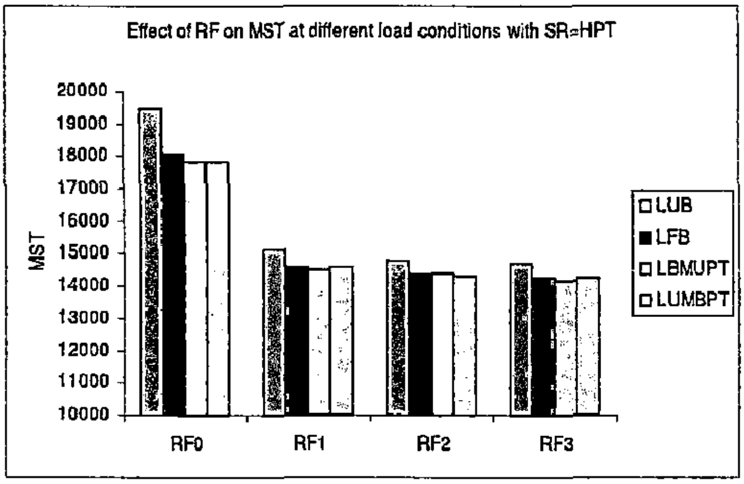


Figure 6.3: MST performance at four levels of RF (V=600, SC=120, SL=BL, SR=HPT)

Table 6.3: MST of different load conditions with SR=HPT at 4 levels of RF

V=600, N=24, SC=120, SL=HPT				
	RF0	**RF1**	**RF2**	**RF3**
LUB	19477.89	15143.38	14805.11	14664.76
LFB	18084.99	14575.85	14342.9	14258.88
LUMBPT	17839.49	14513.03	14381.97	14176.04
LBMUPT	17849.49	14600.21	14278.42	14227.06

Finally we change the sequencing rule to LCFS and observe the performance of the system. Figure 6.4 shows the relationship between MST and routing flexibility for different system load conditions. It is seen that at RF0, MST is maximum for LUB and minimum for LBMUPT. At RF1, MST is maximum for LUB and minimum for LBMUPT. At RF2, MST is maximum for LUB and minimum for LBMUPT. Similarly at RF3 it is observed that MST is maximum for LUB and minimum for LUMBPT. The MST performance improves very much when the system moves from RF0 to RF1. Whereas, there was not very much improvement in the performance of MST with further increase of the routing flexibility level.

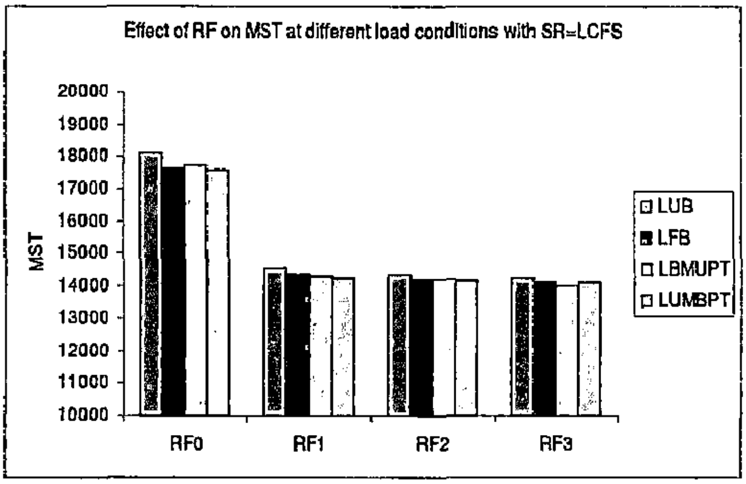


Figure 6.4: MST performance at four levels of RF (V=600, SC=120, SL=BL, SR=LCFS)

Table 6.4: MST of different load conditions with SR=LCFS at 4 levels of RF

V=600, N=24, SC=120, SL=LCFS				
	RF0	**RF1**	**RF2**	**RF3**
LUB	18124.17	14560.62	14353.53	14274.25
LFB	17639.96	14339.21	14194.21	14096.08
LUMBPT	17742.04	14308.59	14190.15	14027.43
LBMUPT	17596.87	14265.47	14163.62	14123.72

It was found that the LUB is having the highest value of MST in all system combinations. Hence this effect is present because the standard deviation of LUB is highest among all the four selected load condition i.e. SD=15.15.

Table 6.5: Comparison of MST at RF and SR for different SLC

Routing Flexibility	Sequencing Rule	V=600, N=24, SC=120; Performance measure: MST	
		Conditions	System Load Conditions
RF0	FCFS	Maximum	LUB
		Minimum	LUMBPT
	SPT	Maximum	LUMBPT
		Minimum	LBMUPT
	HPT	Maximum	LUB
		Minimum	LUMBPT
	LCFS	Maximum	LUB
		Minimum	LUMBPT
RF1	FCFS	Maximum	LUB
		Minimum	LBMUPT
	SPT	Maximum	LUB
		Minimum	LBMUPT
	HPT	Maximum	LUB
		Minimum	LUMBPT
	LCFS	Maximum	LUB
		Minimum	LUMBPT
RF2	FCFS	Maximum	LUB
		Minimum	LFB
	SPT	Maximum	LUB
		Minimum	LUMBPT
	HPT	Maximum	LUB
		Minimum	LUMBPT
	LCFS	Maximum	LUB
		Minimum	LBMUPT
RF3	FCFS	Maximum	LUB
		Minimum	LFB
	SPT	Maximum	LUB
		Minimum	LUMBPT
	HPT	Maximum	LUB
		Minimum	LUMBPT
	LCFS	Maximum	LUB
		Minimum	LUMBPT

Table 6.5 shows the comparison of MST obtained for different sequencing rule and system load conditions. It is observed that system load conditions do affect the MST performance of SFMS for different sequencing rule and different levels of routing flexibility.

6.2.2. Effect of RF on WIP at different system load conditions

In this section we find the effect of routing flexibility on work-in-process (WIP) at different system load conditions. The figures 6.5 to 6.8 are drawn between WIP and routing flexibility at all four system load conditions. Tables 6.6 to 6.9 shows the WIP value at four levels of routing flexibility under four system load conditions and four sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively.

Figure 6.5 shows the impact of routing flexibility under different load conditions at sequencing rule FCFS for 600 parts at a system capacity of 120 on the WIP performance of the system. It is seen from the figure that at RF0, WIP is maximum for LFB and minimum for LUB. At RF1, again WIP is maximum for LFB and minimum for LUB. At RF2, WIP is maximum for LFB and minimum for LBMUPT. Similarly at RF3 it is observed that WIP is maximum for LUMBPT and minimum for LFB. As one adopts different levels of routing flexibility, WIP decreases from RF0 to RF1 and then increases by further increase in the routing flexibility level al almost all system load condition.

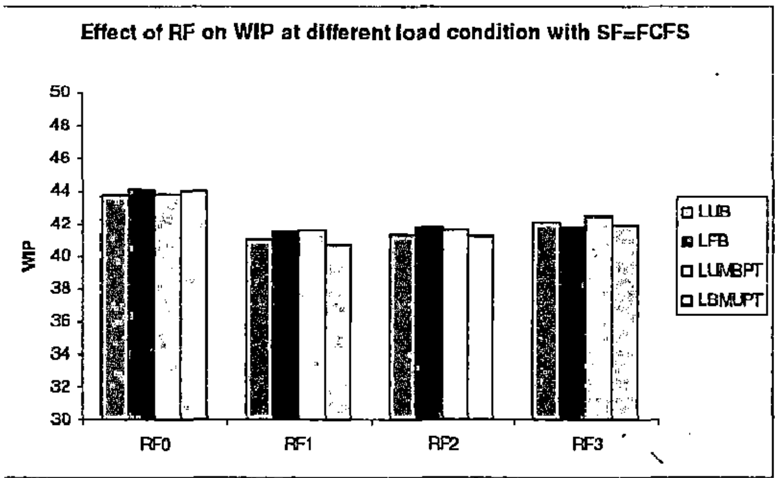


Figure 6.5: WIP performance at four levels of RF (V=600, N=24, SC=120, SR=FCFS)

Table 6.6: WIP of different load conditions with SR=FCFS at 4 levels of RF

V=600, N=24, SC=120, SL=FCFS				
	RF0	RF1	RF2	RF3
LUB	43.73833	41.07667	41.32567	42.11283
LFB	44.11617	41.56033	41.83267	41.82033
LUMBPT	43.8215	41.63183	41.5845	42.48183
LBMUPT	43.95833	40.69833	41.2855	41.86917

Next we change the sequencing rule to SPT and perform the experiment with all other decision parameters keeping same. Figure 6.6 shows the relationship between WIP and routing flexibility at different load conditions. It is seen from the figure that at RF0, WIP is maximum for LUMBPT and minimum for LUB. At RF1, again WIP is maximum for LUMBPT and minimum for LFB. At RF2, WIP is maximum for LUMBPT and minimum for LBMUPT. Similarly at RF3 it is observed that WIP is maximum for LUMBPT and minimum for LBMUPT. The effect of system load at sequencing rule SPT gives a mix response with the increase in the routing flexibility.

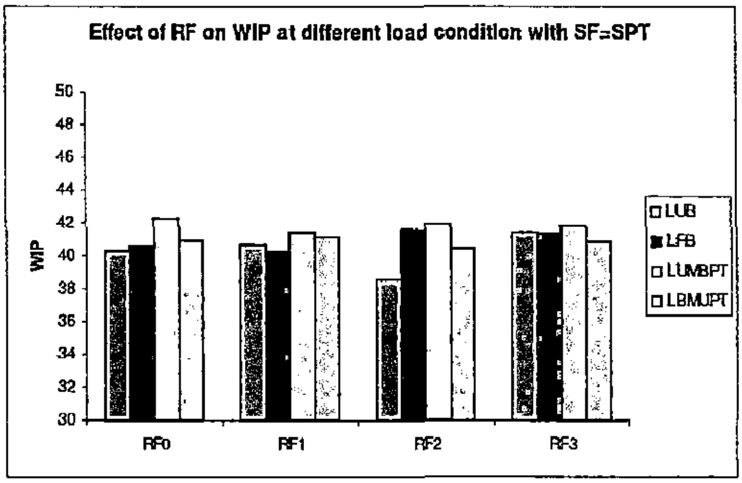


Figure 6.6: WIP performance at four levels of RF (V=600, N=24, SC=120, SR=SPT)

Table 6.7: WIP of different load conditions with SR=SPT at 4 levels of RF

V=600, N=24, SC=120, SL=SPT				
	RF0	RF1	RF2	RF3
LUB	40.31883	40.6435	38.59283	41.42633
LFB	40.56733	40.32033	41.61533	41.37017
LUMBPT	42.27433	41.42883	41.93933	41.80367
LBMUPT	40.90717	41.15533	40.492	40.82433

Now we change the sequencing rule to HPT and observe its impact on the performance of the system. From Figure 6.7 it is seen that at RF0, WIP is maximum for LUB and minimum for LUMBPT. At RF1, again WIP is maximum for LFB and minimum for LUMBPT. At RF2, WIP is maximum for LUB and minimum for LBMUPT. Similarly at RF3 it was observed that WIP is maximum for LFB and minimum for LUMBPT. The WIP decreases when the system moves from RF0 to RF1 and then increases with further increase of the routing flexibility. The maximum decrease in the value of WIP is seen from RF0 to RF1 with the system load condition LUB.

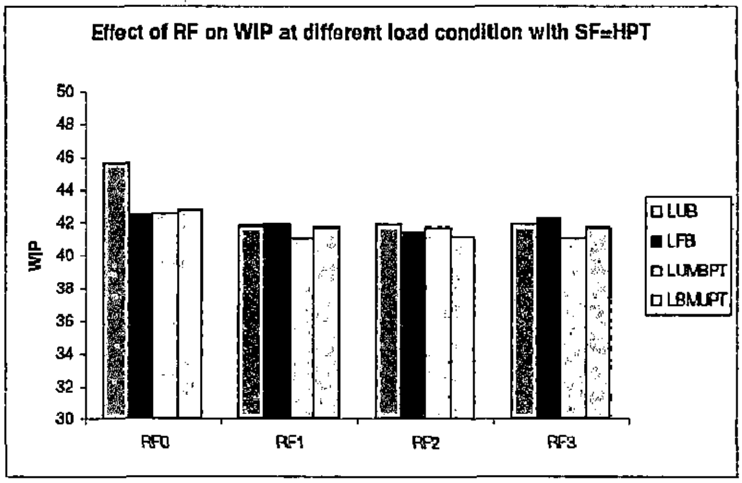


Figure 6.7: WIP performance at four levels of RF (V=600, SC=120, SL=BL, SR=HPT)

Table 6.8: WIP of different load conditions with SR=HPT at 4 levels of RF

V=600, N=24, SC=120, SL=HPT				
	RF0	RF1	RF2	RF3
LUB	45.61867	41.80217	41.93733	41.932
LFB	42.46067	41.8705	41.44483	42.30083
LUMBPT	42.524	41.0305	41.697	41.0105
LBMUPT	42.8025	41.6845	41.10483	41.668

Finally we change the sequencing rule to LCFS and observe the performance of the system. Figure 5.8 shows the relationship between WIP and routing flexibility for different system load conditions. It is seen that at RF0, WIP is maximum for LUMBPT and minimum for LFB. At RF1, WIP is maximum for LFB and minimum for LUB. At RF2, WIP is maximum for LUB and minimum for LBMUPT. Similarly at RF3 it is observed that WIP is maximum for LUMBPT and minimum for LBMUPT. It can also seen from the figure that the value of WIP is highest at RF0 with all load condition and then it decreases for RF1 and then it increases with further increase of routing flexibility.

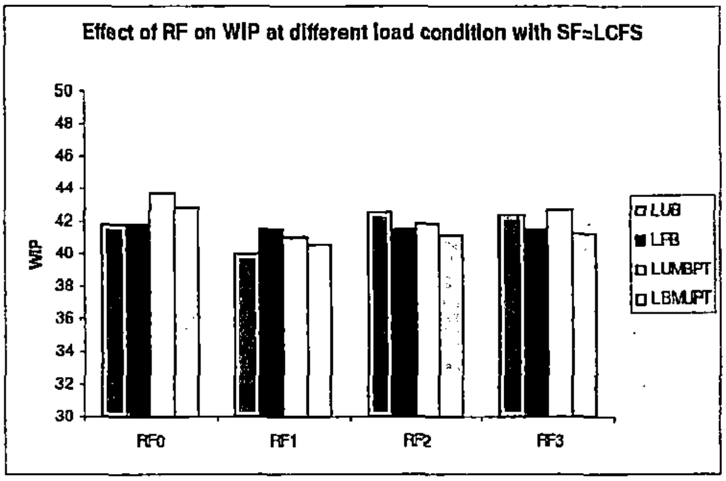


Figure 6.8: WIP performance at four levels of RF (V=600, SC=120, SL=BL, SR=LCFS)

Table 6.9: WIP of different load conditions with SR=LCFS at 4 levels of RF

V=600, N=24, SC=120, SL=LCFS				
	RF0	**RF1**	**RF2**	**RF3**
LUB	41.85533	40.00833	42.5415	42.41367
LFB	41.7925	41.51317	41.55683	41.5685
LUMBPT	43.7235	41.00517	41.90617	42.7755
LBMUPT	42.88583	40.5655	41.101	41.24733

It is clear from the above discussion that the value of WIP improved with the increase in the level of flexibility. The value of WIP indicates that the percentage of time the part is in process.

Table 6.10: Comparison of WIP at RF and SR for different SLC

Routing Flexibility	Sequencing Rule	V=600, N=24, SC=120; Performance measure: WIP	
		Conditions	System Load Conditions
RF0	FCFS.	Maximum	LFB
		Minimum	LUB
	SPT	Maximum	LUMBPT
		Minimum	LUB
	HPT	Maximum	LUB
		Minimum	LUMBPT
	LCFS	Maximum	LUMBPT
		Minimum	LFB
RF1	FCFS	Maximum	LFB
		Minimum	LUB
	SPT	Maximum	LUMBPT
		Minimum	LFB
	HPT	Maximum	LFB
		Minimum	LUMBPT
	LCFS	Maximum	LFB
		Minimum	LUB
RF2	FCFS	Maximum	LFB
		Minimum	LBMUPT
	SPT	Maximum	LUMBPT
		Minimum	LBMUPT
	HPT	Maximum	LUB
		Minimum	LBMUPT
	LCFS	Maximum	LUB
		Minimum	LBMUPT
RF3	FCFS	Maximum	LUMBPT
		Minimum	LFB
	SPT	Maximum	LUMBPT
		Minimum	LBMUPT
	HPT	Maximum	LB
		Minimum	LUMBPT
	LCFS	Maximum	LUMBPT
		Minimum	LBMUPT

Table 6.10 shows the comparison of WIP obtained for different sequencing rule and system load conditions. It is observed that system load conditions do affect the WIP performance of SFMS for different sequencing rule and different levels of routing flexibility.

6.2.3. Effect of RF on RU at different system load conditions

In this section we find the effect of routing flexibility on resource utilization (RU) at different system load conditions. The figures 6.9 to 6.12 are drawn between MST and routing flexibility at all four system load conditions. Tables 6.11 to 6.14 shows the RU value at four levels of routing flexibility under four system load conditions and four sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively. Figure 6.9 shows the impact of routing flexibility under different load conditions at sequencing rule FCFS for 600 parts at a system capacity of 120 on the RU performance of the system. It is seen from the figure that at RF0, RU is maximum for LUMBPT and minimum for LUB. At RF1, RU is maximum for LFB and minimum for LUB. At RF2, RU is maximum for LUMBPT and minimum for LUB. Similarly at RF3 it was observed that RU is maximum for LFB and minimum for LUB. As one adopts different levels of routing flexibility, RU increases from RF0 to RF3 for all system load condition. But this increase in the resource utilization is more visible from RF0 to RF1 at all system load conditions whereas further increase in routing flexibility has a marginal increase in the resource utilization.

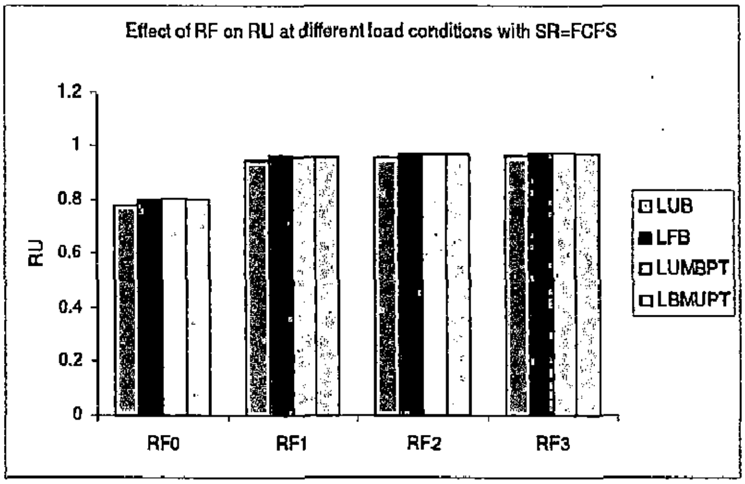


Figure 6.9: RU performance at four levels of RF (V=600, N=24, SC=120, SR=FCFS)

Table 6.11: RU of different load conditions with SR=FCFS at 4 levels of RF

V=600, N=24, SC=120, SR=FCFS				
	RF0	**RF1**	**RF2**	**RF3**
LUB	0.777528	0.94715	0.957915	0.961927
LFB	0.798028	0.960045	0.965402	0.972752
LUMBPT	0.803167	0.958692	0.967028	0.971172
LBMUPT	0.79711	0.958762	0.966008	0.970652

Next we changed the sequencing rule to SPT and perform the experiment with all other decision parameters keeping same. Figure 6.10 shows the relationship between RU and routing flexibility at different load conditions. It is seen from the figure that at RF0, RU is maximum for LUMBPT and minimum for LBMUPT. At RF1, RU is maximum for LFB and minimum for LBMUPT. At RF2, RU is maximum for LUMBPT and minimum for LUB. Similarly at RF3 it was observed that RU is maximum for LFB and minimum for LUB. It is observed from the figure that with the increase in routing flexibility level from RF0 to RF1 the value of RU increases significantly at all system load conditions while in rest of the conditions the value of RU is improved marginally with the increase of routing flexibility. It is also seen form the figure that at higher levels of routing flexibility there is no effect of system load conditions.

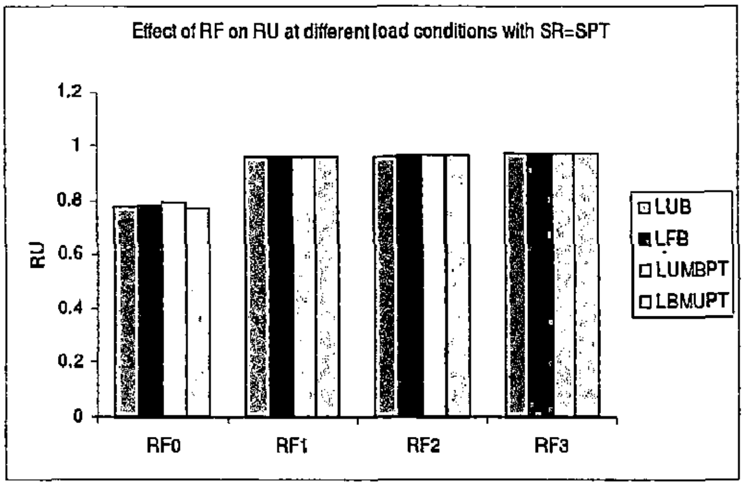


Figure 6.10: RU performance at four levels of RF with V=600, N=24, SC=120, SR=SPT

Table 6.12: RU of different load conditions with SR=SPT at 4 levels of RF

V=600, N=24, SC=120, SR=SPT				
	RF0	**RF1**	**RF2**	**RF3**
LUB	**0.77834**	**0.962718**	**0.965202**	**0.972647**
LFB	**0.783853**	**0.964258**	**0.966098**	**0.97313**
LUMBPT	**0.791837**	**0.962427**	**0.970818**	**0.972903**
LBMUPT	**0.768188**	**0.9618**	**0.969892**	**0.973798**

Now we changed the sequencing rule to HPT and observed its impact on the performance of the system. From Figure 6.11 it is seen that at RF0, RU is maximum for LUMBPT and minimum for LUB. At RF1, again RU is maximum for LUMBPT and minimum for LUB. At RF2, RU is maximum for LBMUPT and minimum for LUB. Similarly at RF3 it is observed that RU is maximum for LUMBPT and minimum for LUB. The RU is improved with the increase of routing flexibility at all load conditions but this increase in RU is more from RF0 to RF1.

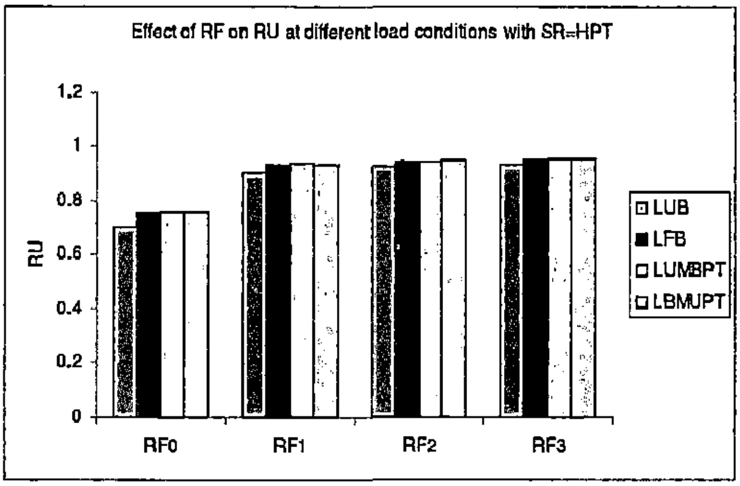


Figure 6.11: RU performance at four levels of RF (V=600, SC=120, SL=BL, SR=HPT)

Table 6.13: RU of different load conditions with SR=HPT at 4 levels of RF

V=600, N=24, SC=120, SR=HPT				
	RF0	**RF1**	**RF2**	**RF3**
LUB	0.702873	0.905477	0.926755	0.93414
LFB	0.753288	0.933293	0.947097	0.953038
LUMBPT	0.76146	0.938675	0.94485	0.959132
LBMUPT	0.756678	0.93265	0.951753	0.955547

Finally we changed the sequencing rule to LCFS and observe the performance of the system. Figure 6.12 shows the relationship between RU and routing flexibility for different system load conditions. It is seen that at RF0, RU is maximum for LBMUPT and minimum for LUB. At RF1, again RU is maximum for LBMUPT and minimum for LUB. At RF2, RU is maximum for LUMBPT and minimum for LUB. Similarly at RF3 it is observed that RU is maximum for LBMUPT and minimum for LUB. It is also seen that RU increases significantly when system shifts from RF0 to RF1 with all system load conditions while in rest of the conditions increase in RU is not very significant with further increase of routing flexibility level.

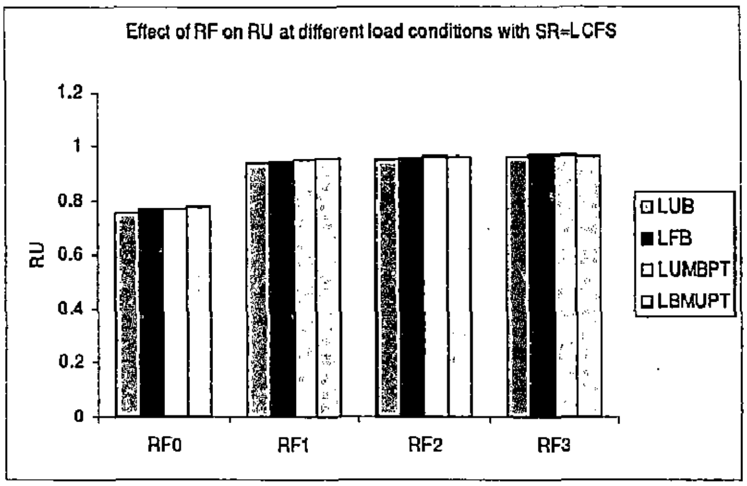


Figure 6.12: RU performance at four levels of RF (V=600, SC=120, SL=BL, SR=LCFS)

Table 6.14: RU of different load conditions with SR=LCFS at 4 levels of RF

V=600, N=24, SC=120, SR=LCFS				
	RF0	**RF1**	**RF2**	**RF3**
LUB	0.756052	0.941475	0.953455	0.959662
LFB	0.770327	0.947528	0.958575	0.965315
LUMBPT	0.768152	0.951953	0.961218	0.970312
LBMUPT	0.774468	0.95387	0.960867	0.961977

From the above discussions it is concluded that the resource utilization is higher at the higher levels of routing flexibility. It is also concluded that the effect of system load condition is more visible at lower levels of routing flexibility in comparison to the higher level of routing flexibility.

Table 6.15: Comparison of RU at RF and SR for different SLC

Routing Flexibility	Sequencing Rule	V=600, N=24, SC=120; Performance measure: RU	
		Conditions	System Load Conditions
RF0	FCFS	Maximum	LUMBPT
		Minimum	LUB
	SPT	Maximum	LUMBPT
		Minimum	LBMUPT
	HPT	Maximum	LUMBPT
		Minimum	LUB
	LCFS	Maximum	LBMUPT
		Minimum	LUB
RF1	FCFS	Maximum	LFB
		Minimum	LUB
	SPT	Maximum	LFB
		Minimum	LBMUPT
	HPT	Maximum	LUMBPT
		Minimum	LUB
	LCFS	Maximum	LBMUPT
		Minimum	LUB
RF2	FCFS	Maximum	LUMBPT
		Minimum	LUB
	SPT	Maximum	LUMBPT
		Minimum	LUB
	HPT	Maximum	LBMUPT
		Minimum	LUB
	LCFS	Maximum	LUMBPT
		Minimum	LUB
RF3	FCFS	Maximum	LFB
		Minimum	LUB
	SPT	Maximum	LFB
		Minimum	LUB
	HPT	Maximum	LUMBPT
		Minimum	LUB
	LCFS	Maximum	LBMUPT
		Minimum	LUB

Table 6.15 shows the comparison of RU obtained for different sequencing rule and system load conditions. It is observed that system load conditions do affect the RU performance of SFMS for different sequencing rule and different levels of routing flexibility

6.2.4. Effect of RF on MST at different sequencing rules

In this section we find the effect of routing flexibility on make-span time (MST) at different sequencing rules. The figures 6.13 to 6.16 are drawn between MST and routing flexibility at all four sequencing rules. Tables 6.16 to 6.19 shows the MST value at four levels of routing flexibility under four sequencing rules i.e. FCFS, SPT, HPT and LCFS and four system load conditions i.e. LUB, LFB, LBMUPT and LUMBPT respectively. Figure 6.13 shows the impact of routing flexibility under sequencing rules at system load condition LUB for 600 parts at a system capacity of 120 on the MST performance of the system. It is seen from the figure that at RF0, MST is maximum for HPT and minimum for FCFS. At RF1, MST is maximum for HPT and minimum for SPT. At RF2, MST is maximum for HPT and minimum for SPT. Similarly at RF3 it is observed that MST is maximum for HPT and minimum for SPT. As one adopts different levels of routing flexibility, MST decreases from RF0 to RF3 for all sequencing rules. But this decrease in MST is more from RF0 to RF1 while from RF1 onwards the decrease in MST is very insignificant. It is also observed from the figure that the sequencing rule HPT has the highest value among all sequencing rules at all four routing flexibility levels.

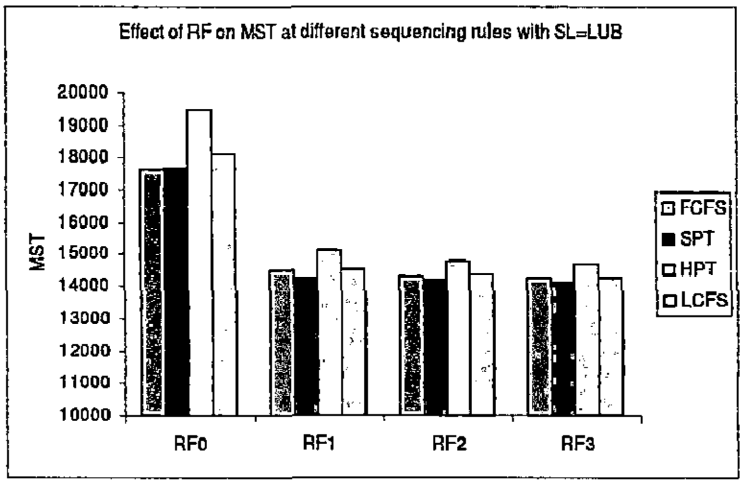


Figure 6.13: MST performance at four levels of RF (V=600, N=24, SC=120, SL=LFB)

Table 6.16: MST of different sequencing rules with SL=LFB at 4 levels of RF

V=600, N=24, SC=120, SL=LUB				
	RF0	RF1	RF2	RF3
FCFS	17609.79	14480.1	14320.61	14270.25
SPT	17701.78	14244.43	14207.43	14120.99
HPT	19477.89	15143.38	14805.11	14664.76
LCFS	18124.17	14560.62	14353.53	14274.25

Next we changed the system load to LFB and perform the experiment with all other decision parameters keeping same. Figure 6.14 shows the relationship between MST and routing flexibility at different sequencing rules. It is seen from the figure that at RF0, MST is maximum for HPT and minimum for FCFS. At RF1, again MST is maximum for HPT and minimum for SPT. At RF2, MST is maximum for HPT and minimum for FCFS. Similarly at RF3 it is observed that MST is maximum for HPT and minimum for FCFS. With increase in routing flexibility level MST decreases for all the sequencing rules. The improvement in the MST is much visible in the figure from RF0 to RF1 at all sequencing rule. The effect of sequencing rules has an impact at initial level of routing flexibility whereas at RF3 this impact diminished.

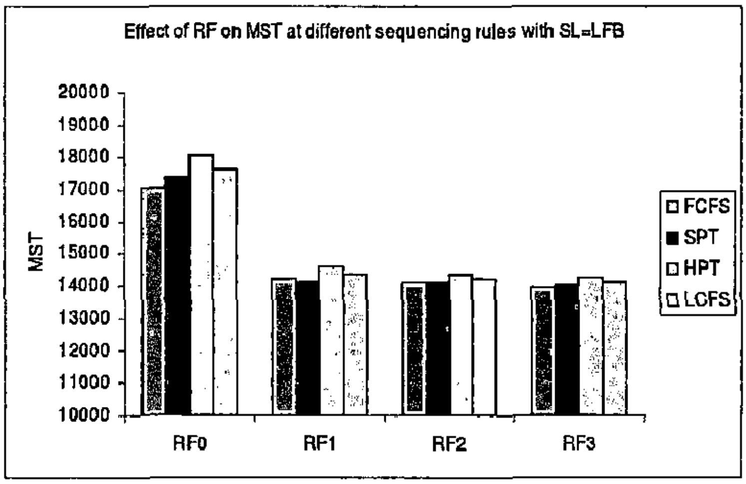


Figure 6.14: MST performance at four levels of RF (V=600, N=24, SC=120, SL=LUB)

Table 6.17: MST of different sequencing rules with SL=LUB at 4 levels of RF

V=600, N=24, SC=120, SL=LFB				
	RF0	**RF1**	**RF2**	**RF3**
FCFS	17038.06	14201.38	14103.08	13963.16
SPT	17367.37	14129.01	14105.43	13989.24
HPT	18084.99	14575.85	14342.9	14258.88
LCFS	17639.96	14339.21	14194.21	14096.08

Now we changed the system load to LBMUPT and observe its impact on the performance of the system. From Figure 6.15 it is seen that at RF0, MST is maximum for HPT and minimum for FCFS. At RF1, again MST is maximum for HPT and minimum for SPT. At RF2, MST is maximum for HPT and minimum for SPT. Similarly at RF3 it is observed that MST is maximum for HPT and minimum for SPT. The MST is improved with the increase of routing flexibility at all sequencing rules but it is seen that the improvement is more visible from RF0 to RF1 at all sequencing rules. The further increase in the routing flexibility level dose not has any significant improvement in the MST. It is also observed that the impact of sequencing rule is more at RF0 in compare to the other levels of routing flexibility.

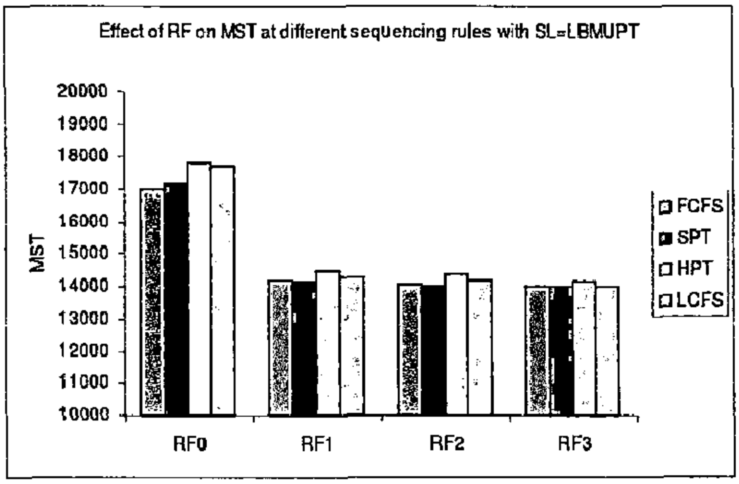


Figure 6.15: MST performance at four levels of RF (V=600, N=24, SC=120, SL= LBMUPT)

Table 6.18: MST of different sequencing rules with SL= LBMUPT at 4 levels of RF

V=600, N=24, SC=120, SL=LBMUPT				
	RF0	**RF1**	**RF2**	**RF3**
FCFS	17054.12	14177.62	14091.17	14010.95
SPT	17727.18	14118.76	14037.58	13971.13
HPT	17839.49	14600.21	14278.42	14227.06
LCFS	17596.87	14265.47	14163.62	14123.72

Finally we change the system load to LUMBPT and observe the performance of the system. Figure 6.16 shows the relationship between MST and routing flexibility for different sequencing rules. It is seen that at RF0, MST is maximum for HPT and minimum for FCFS. At RF1, again MST is maximum for HPT and minimum for SPT. At RF2, MST is maximum for HPT and minimum for SPT. Similarly at RF3 it is observed that MST is maximum for HPT and minimum for SPT. It is also seen that MST decreases when system shifts from RF0 to RF1 at all four sequencing rule significantly and then the reduction in MST is not very significant by further increase in the level of routing flexibility. The sequencing rule SPT gives best performance at all levels of routing flexibility except RF0 where FCFS gives better performance.

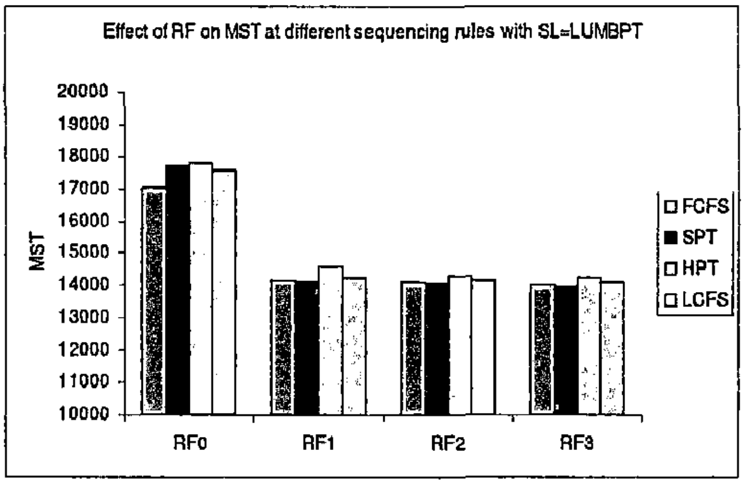


Figure 6.16 MST performance at four levels of RF (V=600, N=24, SC=120, SL= LUMBPT)

Table 6.19: MST of different sequencing rules with SL= LUMBPT at 4 levels of RF

V=600, N=24, SC=120, SL=LUMBPT				
	RF0	**RF1**	**RF2**	**RF3**
FCFS	16985.09	14208.57	14046.53	14016
SPT	17216	14142.75	14018.37	13993.91
HPT	17839.49	14513.03	14381.97	14176.04
LCFS	17742.04	14308.59	14190.15	14027.43

From the above discussion it is found that the MST decreases with the increase of routing flexibility. It also reveals that the improvement in MST is very significant when the SFM system shifts from RF0 to RF1 and then this improvement is diminishesed with the further increase of routing flexibility and the effect of sequencing rules was very much visible at lower level of routing flexibility in comparison to the higher level of routing flexibility at all system load conditions. This variation in the MST is present because, at lower level of routing flexibility the formation of queue is more likely in comparison to the higher level of routing flexibility.

Table 6.20: Comparison of MST at RF and SR for different SLC

Routing Flexibility	System load condition	V=600, N=24, SC=120; Performance measure: MST	
		Conditions	Sequencing rule
RF0	LUB	Maximum	HPT
		Minimum	FCFS
	LFB	Maximum	HPT
		Minimum	FCFS
	LBMUPT	Maximum	HPT
		Minimum	FCFS
	LUMBPT	Maximum	HPT
		Minimum	FCFS
RF1	LUB	Maximum	HPT
		Minimum	SPT
	LFB	Maximum	HPT
		Minimum	SPT
	LBMUPT	Maximum	HPT
		Minimum	SPT
	LUMBPT	Maximum	HPT
		Minimum	SPT
RF2	LUB	Maximum	HPT
		Minimum	SPT
	LFB	Maximum	HPT
		Minimum	FCFS
	LBMUPT	Maximum	HPT
		Minimum	SPT
	LUMBPT	Maximum	HPT
		Minimum	SPT
RF3	LUB	Maximum	HPT
		Minimum	SPT
	LFB	Maximum	HPT
		Minimum	FCFS
	LBMUPT	Maximum	HPT
		Minimum	SPT
	LUMBPT	Maximum	HPT
		Minimum	SPT

Table 6.20 shows the comparison of MST obtained for different sequencing rule and system load conditions. It is observed that system load conditions do affect the MST performance of SFMS for different sequencing rule and different levels of routing flexibility.

6.2.5. Effect of RF on WIP at different sequencing rules

In this section we find the effect of routing flexibility on work-in-process (WIP) at different sequencing rules. The figures 6.17 to 6.20 are drawn between WIP and routing flexibility at all four sequencing rules. Tables 6.21 to 6.24 shows the WIP value at four levels of routing flexibility under four sequencing rules i.e. FCFS, SPT, HPT and LCFS and four system load conditions i.e. LUB, LFB, LBMUPT and LUMBPT respectively. Figure 6.17 shows the impact of routing flexibility under different sequencing rules at system load LUB for 600 parts at a system capacity of 120 on the WIP performance of the system. It is seen from the figure that at RF0, WIP is maximum for HPT and minimum for SPT. At RF1, again WIP is maximum for HPT and minimum for LCFS. At RF2, WIP is maximum for HPT and minimum for SPT. Similarly at RF3 it is observed that WIP is maximum for LCFS and minimum for FCFS. As one adopts different levels of routing flexibility, WIP decreases from RF0 to RF1 for almost all sequencing rules except SPT significantly and then it increases marginally.

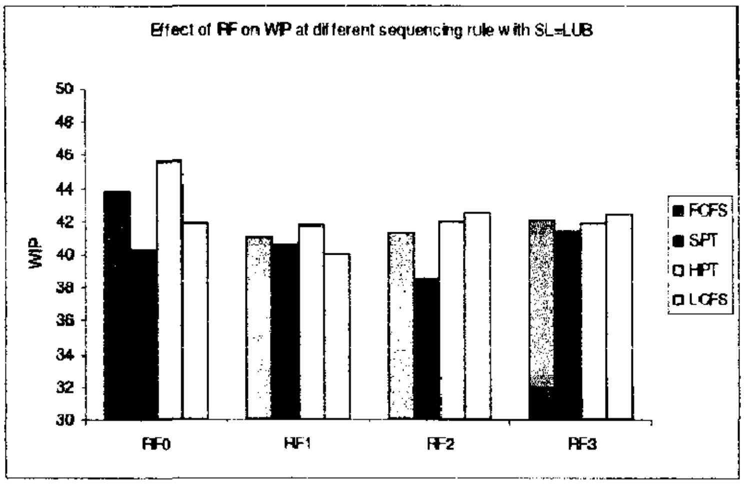


Figure 6.17: MST performance at four levels of RF (V=600, N=24, SC=120, SL= LUB)

Table 6.21: WIP of different sequencing rules with SL= LUB at 4 levels of RF

V=600, N=24, SC=120, SL=LUB				
	RF0	**RF1**	**RF2**	**RF3**
FCFS	43.73833	41.07667	41.32567	42.11283
SPT	40.31883	40.6435	38.59283	41.42633
HPT	45.61867	41.80217	41.93733	41.932
LCFS	41.85533	40.00833	42.5415	42.41367

Next we changed the system load to LFB and perform the experiment with all other decision parameters keeping same. Figure 6.18 shows the relationship between WIP and routing flexibility at different sequencing rules. It is seen from the figure that at RF0, WIP is maximum for FCFS and minimum for SPT. At RF1, WIP is maximum for HPT and minimum for SPT. At RF2, WIP is maximum for FCFS and minimum for HPT. Similarly at RF3 it is observed that WIP is maximum for HPT and minimum for SPT. With increase in routing flexibility level WIP initially decrease with the increase of routing flexibility for almost all sequencing rules and then it increase very marginally from RF2 to RF3.

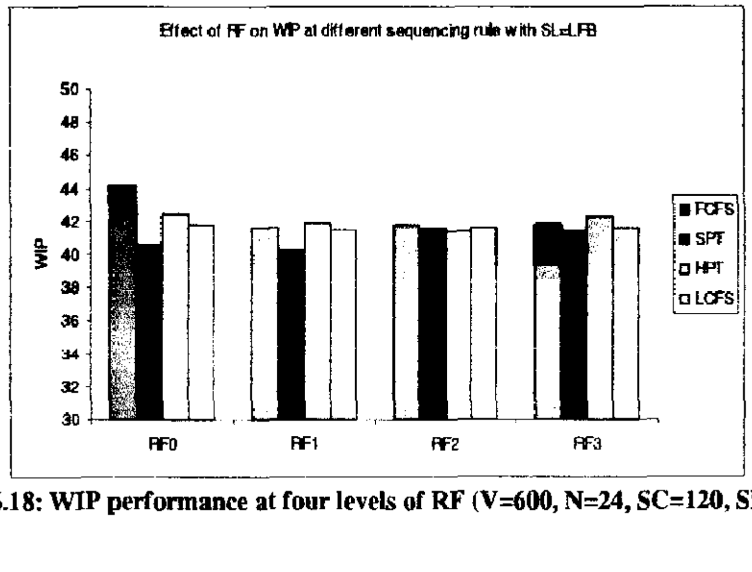


Figure 6.18: WIP performance at four levels of RF (V=600, N=24, SC=120, SL= LFB)

Table 6.22: WIP of different sequencing rules with SL= LFB at 4 levels of RF

V=600, N=24, SC=120, SL=LFB				
	RF0	RF1	RF2	RF3
FCFS	44.11617	41.56033	41.83267	41.82033
SPT	40.56733	40.32033	41.61533	41.37017
HPT	42.46067	41.8705	41.44483	42.30083
LCFS	41.7925	41.51317	41.55683	41.5685

Now we changed the system load to LBMUPT and observe its impact on the performance of the system. From Figure 6.19 it is seen that at RF0, WIP is maximum for FCFS and minimum for SPT. At RF1, WIP is maximum for HPT and minimum for LCFS. At RF2, WIP is maximum for FCFS and minimum for SPT. Similarly at RF3 it is observed that WIP is maximum for FCFS and minimum for SPT. The WIP is decreased with the increase of routing flexibility at all sequencing rules except SPT from RF0 to RF1 as well from RF1 to RF2 almost in all conditions but it is seen that from RF2 to RF3 the value of WIP increases marginally at all sequencing rules.

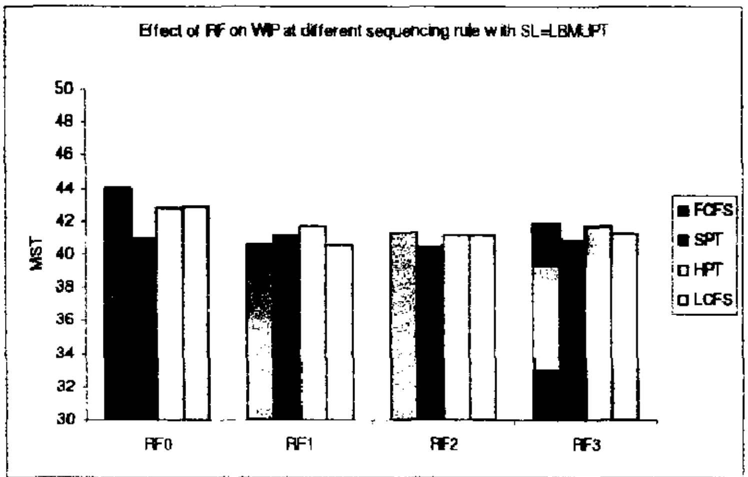


Figure 6.19: WIP performance at four levels of RF (V=600, N=24, SC=120, SL= LBMUPT)

Table 6.23: WIP of different sequencing rules with SL= LBMUPT at 4 levels of RF

V=600, N=24, SC=120, SL=LBMUPT				
	RF0	RF1	RF2	RF3
FCFS	43.95833	40.69833	41.2855	41.86917
SPT	40.90717	41.15533	40.492	40.82433
HPT	42.8025	41.6845	41.10483	41.668
LCFS	42.88583	40.5655	41.101	41.24733

Finally we changed the system load to LUMBPT and observe the performance of the system. Figure 6.20 shows the relationship between WIP and routing flexibility for different sequencing rules. It is seen that at RF0, WIP is maximum for FCFS and minimum for SPT. At RF1, again WIP is maximum for FCFS and minimum for LCFS. At RF2, WIP is maximum for SPT and minimum for FCFS. Similarly at RF3 it is observed that WIP is maximum for LCFS and minimum for HPT. It is seen from the figure that the WIP decreases significantly from RF0 to RF1 at all sequencing rules and then increases marginally with the increases of routing flexibility level almost with all sequencing rules.

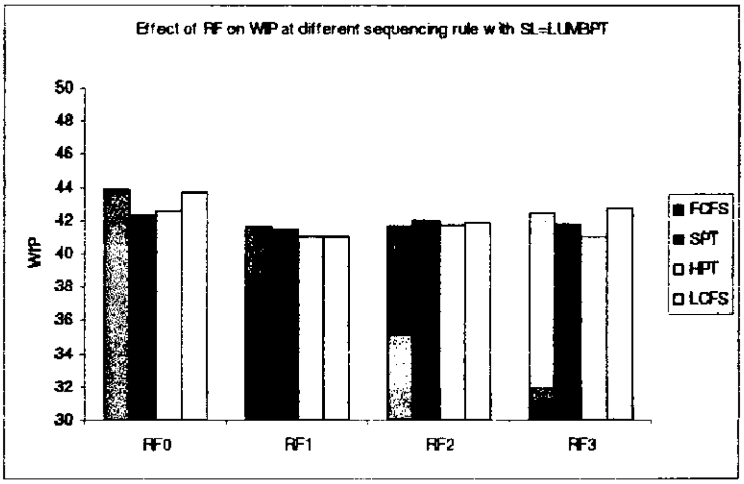


Figure 6.20: WIP performance at four levels of RF (V=600, N=24, SC=120, SL= LUMBPT)

Table 6.24: WIP of different sequencing rules with SL= LUMBPT at 4 levels of RF

V=600, N=24, SC=120, SL=LUMBPT				
	RF0	**RF1**	**RF2**	**RF3**
FCFS	43.8215	41.63183	41.5845	42.48183
SPT	42.27433	41.42883	41.93933	41.80367
HPT	42.524	41.0305	41.697	41.0105
LCFS	43.7235	41.00517	41.90617	42.7755

It is clear from the above discussion that the value of WIP improved with the increase in the level of routing flexibility. Table 6.25 shows the comparison of WIP obtained for different sequencing rule and system load conditions. It was observed that system load conditions do affect the WIP performance of SFMS for different sequencing rule and different levels of routing flexibility.

Table 6.25: Comparison of WIP at RF and SR for different SLC

Routing Flexibility	System load condition	V=600, N=24, SC=120; Performance measure: WIP	
		Conditions	Sequencing rule
RF0	LUB	Maximum	HPT
		Minimum	SPT
	LFB	Maximum	FCFS
		Minimum	SPT
	LBMUPT	Maximum	FCFS
		Minimum	SPT
	LUMBPT	Maximum	FCFS
		Minimum	SPT
RF1	LUB	Maximum	HPT
		Minimum	FCFS
	LFB	Maximum	HPT
		Minimum	SPT
	LBMUPT	Maximum	HPT
		Minimum	LCFS
	LUMBPT	Maximum	FCFS
		Minimum	LCFS
RF2	LUB	Maximum	HPT
		Minimum	SPT
	LFB	Maximum	FCFS
		Minimum	HPT
	LBMUPT	Maximum	FCFS
		Minimum	SPT
	LUMBPT	Maximum	SPT
		Minimum	FCFS
RF3	LUB	Maximum	LCFS
		Minimum	FCFS
	LFB	Maximum	HPT
		Minimum	SPT
	LBMUPT	Maximum	FCFS
		Minimum	SPT
	LUMBPT	Maximum	LCFS
		Minimum	HPT

6.2.6. Effect of RF on RU at different sequencing rules

In this section we find the effect of routing flexibility on resource utilization (RU) at different sequencing rules. The figures 6.21 to 6.24 are drawn between RU and routing flexibility at all four sequencing rules. Tables 6.26 to 6.29 shows the RU value at four levels of routing flexibility under four sequencing rules i.e. FCFS, SPT, HPT and LCFS and four system load conditions i.e. LUB, LFB, LBMUPT and LUMBPT respectively.

Figure 6.21 shows the impact of routing flexibility under different sequencing rules at system load LUB for 600 parts at a system capacity of 120 on the RU performance of the system. It is seen from the figure that at RF0, RU is maximum for SPT and minimum for HPT. At RF1, again RU is maximum for SPT and minimum for HPT. At RF2, RU is maximum for SPT and minimum for HPT. Similarly at RF3 it is observed that RU is maximum for SPT and minimum for HPT. It is seen from the figure that the effect of sequencing rules are almost same at all levels of routing flexibility. It is also found that the sequencing rule SPT has the highest value of resource utilization at all levels of routing flexibility.

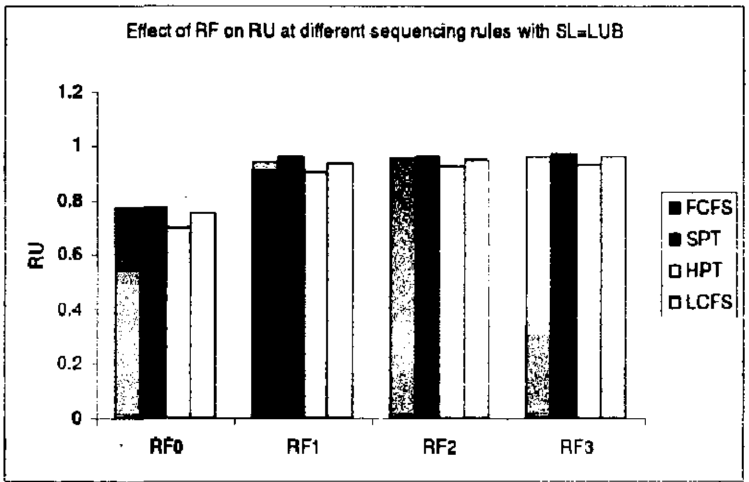


Figure 6.21: RU performance at four levels of RF (V=600, N=24, SC=120, SL= LUB)

Table 6.26: RU of different sequencing rules with SL= LFB at 4 levels of RF

V=600, N=24, SC=120, SL=LUB				
	RF0	RF1	RF2	RF3
FCFS	0.777528	0.94715	0.957915	0.961927
SPT	0.77834	0.962718	0.965202	0.972647
HPT	0.702873	0.905477	0.926755	0.93414
LCFS	0.756052	0.941475	0.953455	0.959662

Next we changd the system load to LFB and perform the experiment with all other decision parameters keeping same. Figure 6.22 shows the relationship between RU and routing flexibility at different sequencing rules. It is seen from the figure that at RF0, RU is maximum for FCFS and minimum for HPT. At RF1, RU is maximum for SPT and minimum for HPT. At RF2, RU is maximum for SPT and minimum for HPT. Similarly at RF3 it is observed that RU is maximum for SPT and minimum for HPT. The increase in the RU is more from RF0 to RF1 while further increase in the routing flexibility does not have very significant effect on the RU. It was also seen from the figure that the trend of sequencing rules is almost same at all levels of routing flexibility except at RF0.

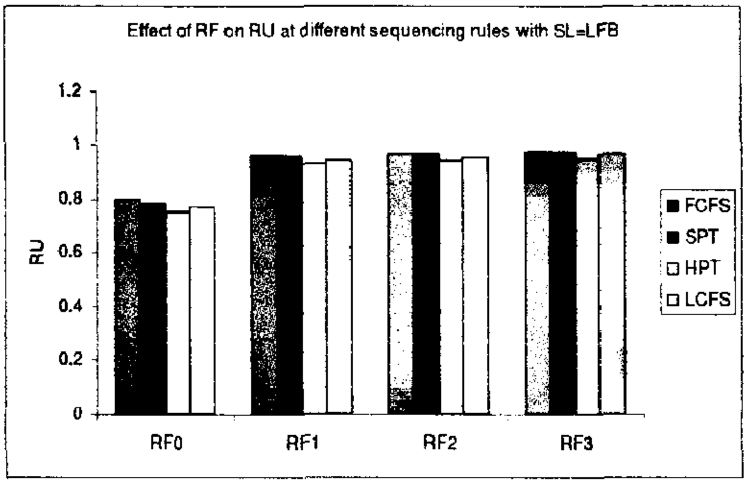


Figure 6.22: RU performance at four levels of RF (V=600, N=24, SC=120, SL= LFB)

Table 6.27: RU of different sequencing rules with SL= LFB at 4 levels of RF

V=600, N=24, SC=120, SL=LFB				
	RF0	**RF1**	**RF2**	**RF3**
FCFS	0.798028	0.960045	0.965402	0.972752
SPT	0.783853	0.964258	0.966098	0.97313
HPT	0.753288	0.933293	0.947097	0.953038
LCFS	0.770327	0.947528	0.958575	0.965315

Now we changed the system load to LBMUPT and observe its impact on the performance of the system. From Figure 6.23 it was seen that at RF0, RU is maximum for FCFS and minimum for HPT. At RF1, RU is maximum for SPT and minimum for

HPT. At RF2, RU is maximum for SPT and minimum for HPT. Similarly at RF3 it was observed that RU is maximum for SPT and minimum for HPT. The RU is improved with the increase of routing flexibility at all sequencing rules. But this improvement in the RU is more visible when the system shifts from RF0 to RF1 and then the improvement is insignificant with all sequencing rules.

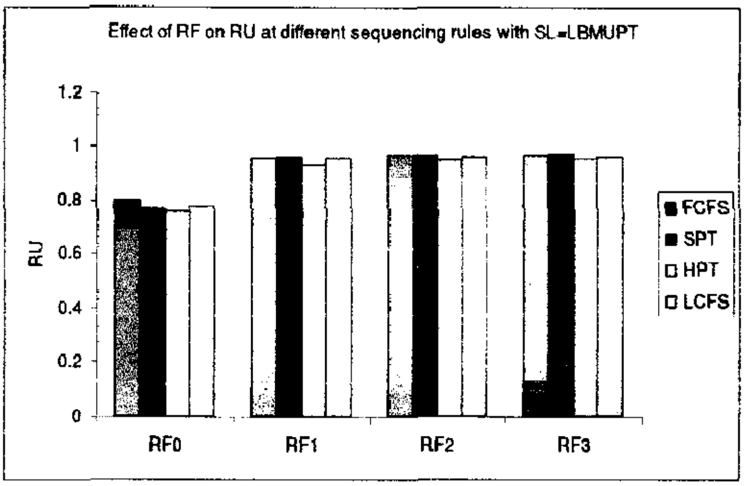


Figure 6.23: RU performance at four levels of RF (V=600, N=24, SC=120, SL= LBMUPT)

Table 6.28: RU of different sequencing rules with SL= LUMBPT at 4 levels of RF

V=600, N=24, SC=120, SL=LBMUPT				
	RF0	**RF1**	**RF2**	**RF3**
FCFS	0.79711	0.958762	0.966008	0.970652
SPT	0.768188	0.9618	0.969892	0.973798
HPT	0.756678	0.93265	0.951753	0.955547
LCFS	0.774468	0.95387	0.960867	0.961977

Finally we changed the system load to LUMBPT and observe the performance of the system. Figure 6.24 shows the relationship between RU and routing flexibility for different sequencing rules. It was seen that at RF0, RU is maximum for FCFS and minimum for HPT. At RF1, RU is maximum for SPT and minimum for HPT. At RF2, RU is maximum for SPT and minimum for HPT. Similarly at RF3 it was observed that RU is maximum for SPT and minimum for HPT. It is seen that RU increases with the increase of routing flexibility. It is also observed that the effect of sequencing rules are more visible at lower level of routing flexibility in compare to higher level of routing flexibility.

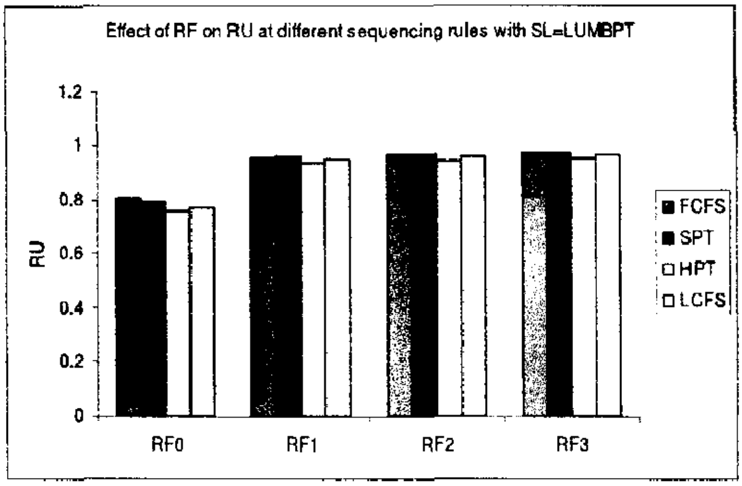


Figure 6.24: RU performance at four levels of RF (V=600, N=24, SC=120, SL=LUMBPT)

Table 6.29: RU of different sequencing rules with SL= LBMUPT at 4 levels of RF

V=600, N=24, SC=120, SL=LUMBPT				
	RF0	**RF1**	**RF2**	**RF3**
FCFS	0.803167	0.958692	0.967028	0.971172
SPT	0.791837	0.962427	0.970818	0.972903
HPT	0.76146	0.938675	0.94485	0.959132
LCFS	0.768152	0.951953	0.961218	0.970312

From the above discussions it is concluded that the maximum improvement in the value of resource utilization is available when the system shift from RF0 to RF1. It was also observed that the impact of sequencing rules on the resource utilization has more effect at lower levels of routing flexibility and the effect of sequencing rules reduces as we move towards the higher level of routing flexibility.

Table 6.31 shows the comparison of RU obtained for different sequencing rule and system load conditions. It is observed that system load conditions do affect the RU performance of SFMS for different sequencing rule and different levels of routing flexibility.

Table 6.30: Comparison of RU at RF and SR for different SLC

Routing Flexibility	System load condition	V=600, N=24, SC=120; Performance measure: RU	
		Conditions	Sequencing rule
RF0	LUB	Maximum	SPT
		Minimum	HPT
	LFB	Maximum	FCFS
		Minimum	HPT
	LBMUPT	Maximum	FCFS
		Minimum	HPT
	LUMBPT	Maximum	FCFS
		Minimum	HPT
RF1	LUB	Maximum	SPT
		Minimum	HPT
	LFB	Maximum	SPT
		Minimum	HPT
	LBMUPT	Maximum	SPT
		Minimum	HPT
	LUMBPT	Maximum	SPT
		Minimum	HPT
RF2	LUB	Maximum	SPT
		Minimum	HPT
	LFB	Maximum	SPT
		Minimum	HPT
	LBMUPT	Maximum	SPT
		Minimum	HPT
	LUMBPT	Maximum	SPT
		Minimum	HPT
RF3	LUB	Maximum	SPT
		Minimum	HPT
	LFB	Maximum	SPT
		Minimum	HPT
	LBMUPT	Maximum	SPT
		Minimum	HPT
	LUMBPT	Maximum	SPT
		Minimum	HPT

6.3. Conclusion

In this chapter, the simulation experiments were carried out with four load conditions (i.e. LUB, LFB, LBMUPT, and LUMBPT) and four sequencing rules (i.e.

FCFS, SPT, HPT, and LCFS) at four levels of routing flexibility. The performance of the system was measured by three parameters such as MST, WIP resource utilization. In the result it was found that the performance was improved with the increase of routing flexibility in all of the combinations but this increase of the performance is more when the SFMS system was shifted from RF0 to RF1.

Further, it is concluded that the sequencing rules at the queue also has some effect on the performance of the system. It is found that this effect is more at lower level of routing flexibility because the formation of queue is more likely at lower level of routing flexibility. Hence, from the above discussion the sequencing rule SPT has the best performance among the four selected sequencing rules in the above selected combinations.

Chapter 7

Performance of SFMS with the use of AGVs

7.1 Introduction

In Chapter 3, we have stated the main objectives of this thesis. The objectives were to enrich stochastic flexible manufacturing system (SFMS) in the domain of FMS operating with different design, planning and control decisions. All these decisions are implemented in phased manner. In the first phase design decisions considered was sequencing flexibility and system capacity (buffer size), planning decisions include different system load conditions and system configurations and control decisions include dispatching and sequencing rules while in the second phase the routing flexibility is considered as the design decision by maintaining the other factors as same. In Chapter 4, based on the motivation and objectives as stated in Chapter 3, we developed the conceptual model for SFMS.

This chapter focuses on a simulation-based experimental study of the interaction among number of AGVs, AGV velocity, part sequencing rules and system capacity in a typical SFMS manufacturing system. Three important decisions are considered for experimentation. Design decision considered are number of AGVs (1, 2, 3 and 4) and system capacity level is taken as 120 (buffer size = 20). Planning decision include one system load conditions i.e. load fully balanced (LFB), Control decisions include four sequencing rules (FCFS, SPT, HPT and LCFS) and AGV velocity (2, 4, 6 and 8 m/s). The performance of the system was evaluated using performance measures such as makespan time, work-in-process, and average resource utilization. The stochastic environment was developed by providing normal distribution for processing time, and exponential distribution for inter-arrival time of parts in the system.

Simulation model for SFMS is developed in Arena simulation software. The developed models are used to conduct a series of experiments to investigate the effects of number of AGVs in the fleet, AGV velocity, system capacity and part sequencing rules. In the stochastic environment of a SFMS the simulation experimentation first involves determining the study data set. For this a number of experimental sets were performed with different number of replications in each set as discussed in the chapter 5. So in view of this observation it was decided to take 15 replications for each set of experiment. The average of the results obtained from 15 replications is used for analysis purpose.

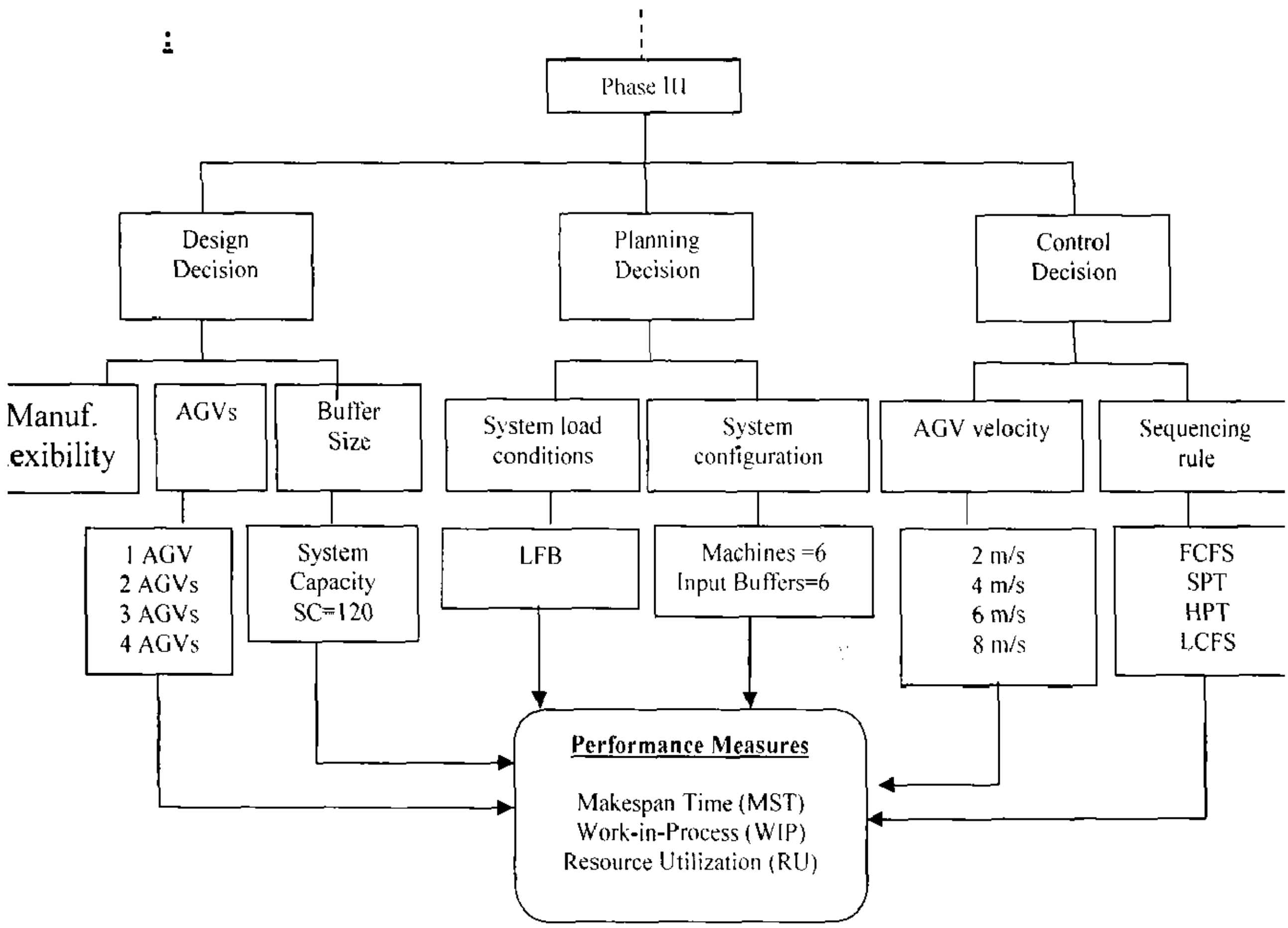


Figure 7.0: Salient features of the study of phase III

7.2 Simulation results with AGVs

As stated earlier SFMS was developed under phased manner. In the first phase we considered sequencing flexibility as design decision while in the second phase routing flexibility was considered as design decision by maintaining the other factors constant. Here in this phase we consider number of AGVs as design decision. The impact of number of AGVs on the performance of SFMS was evaluated under different planning and control decisions as shown in the figure 7.0.

7.2.1. Effect of number of AGVs on MST at different sequencing rules

In this section we found the effect of number of AGVs on makespan (MST) at four different sequencing rules that are FCFS, SPT, HPT, and LCFS in stochastic environment. The figures 7.1, 7.2, 7.3 and 7.4 are drawn between MST and different number of AGVs and values of velocities at all four sequencing rules respectively. MST is collected for the total of 600 parts with system capacity equal to 120.

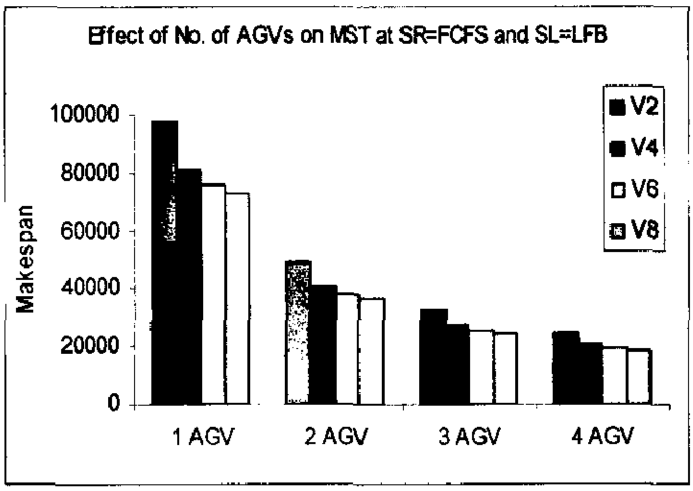


Figure 7.1: MST performance at different levels of AGVs and velocities (V=600, N=24, SC=120, SR=FCFS, SL=LFB)

It is seen from the figure 7.1 that for FCFS sequencing rule and for 1 AGV, MST is maximum for velocity 2 m/s and it decreases with the increase in velocity. It is observed that velocity of 8 m/s the MST is minimum. At 2 AGVs, 3 AGVs and 4 AGVs the same trend is observed as observed for 1 AGV. It is further observed from the figure 1 that the of MST decreases with the increase in the number of AGVs in the system. This is because with increase in the number of AGVs the parts wait less hence reducing MST.

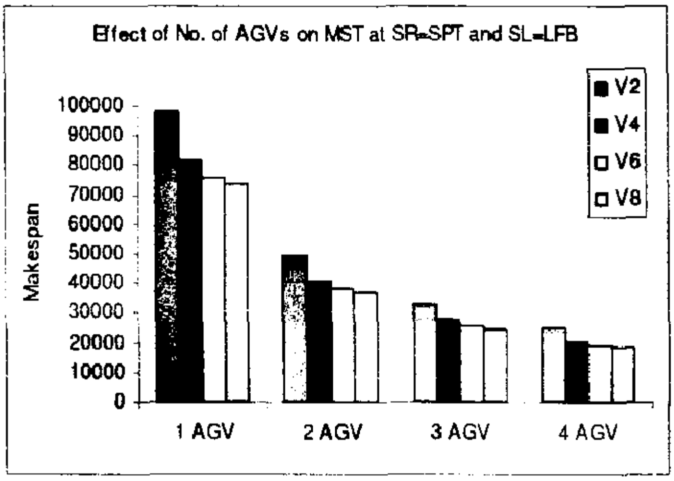


Figure 7.2: MST performance at different levels of AGVs and velocities (V=600, N=24, SC=120, SR=SPT, SL=LFB)

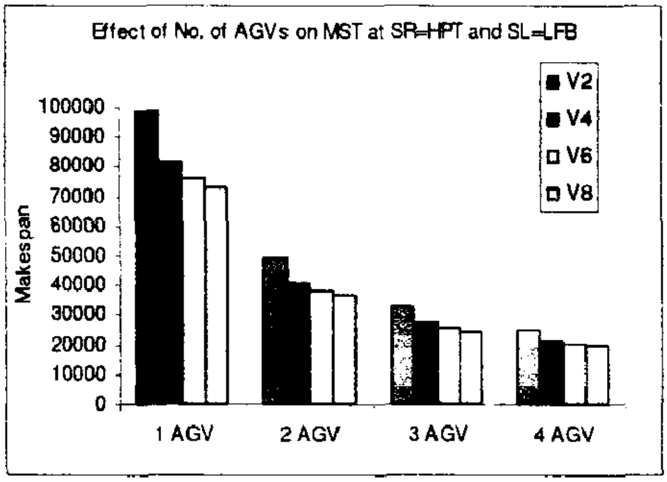


Figure 7.3: MST performance at different levels of AGVs and velocities (V=600, N=24, SC=120, SR=HPT, SL=LFB)

Almost similar trends are observed when sequencing rule is changed to SPT, HPT and LCFS (see Figure 7.2, 7.3 and 7.4).

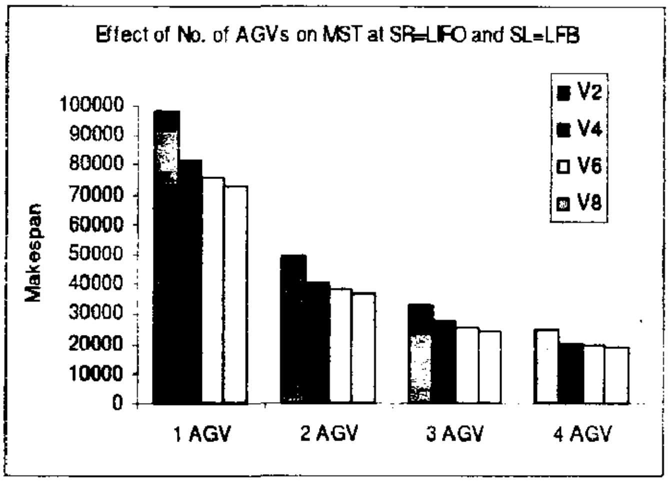


Figure 7.4: MST performance at different levels of AGVs and velocities (V=600, N=24,SC=120, SR=LCFS, SL=LFB)

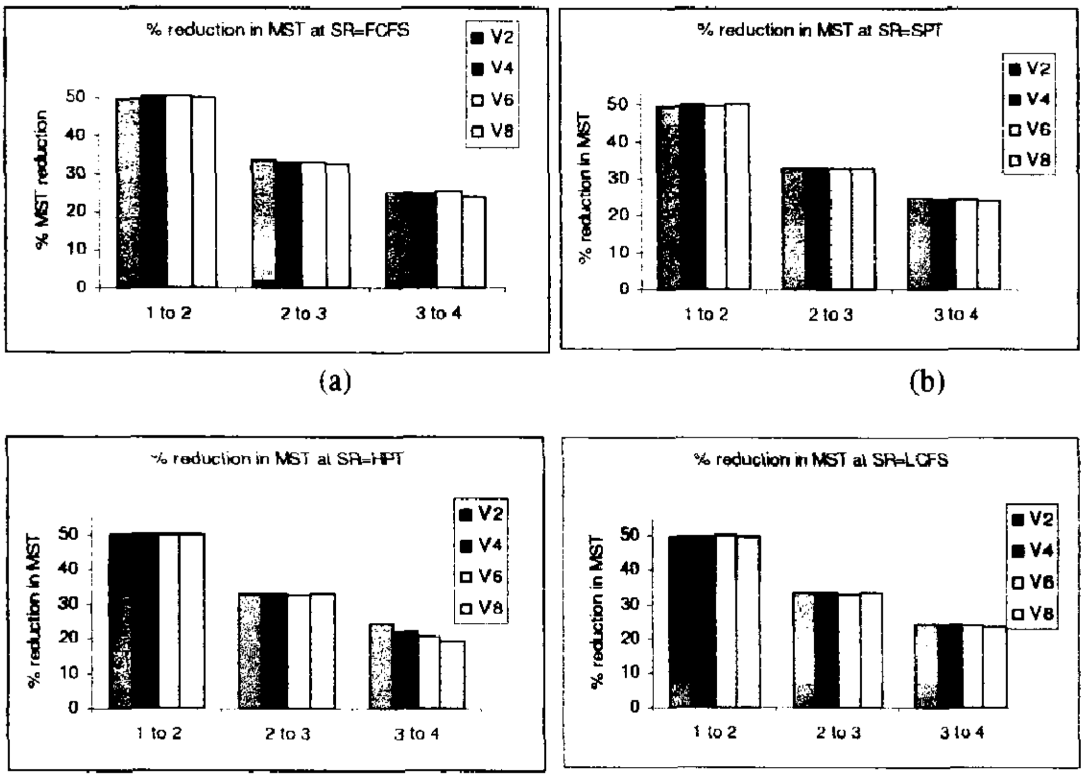
Table 7.1 shows the MST for all combination of number of AGVs, velocities and sequencing rules. Table 7.2 shows the percentage reduction in MST at different levels of AGVs and velocities.

Table 7.1: MST performance at different levels of AGVs and velocities

SR=FCFS, SL=LFB, N=24				
MST	V2	V4	V6	V8
1 AGV	97429.53	81686.85	76379.79	72840.83
2 AGVs	49273.74	40826.92	38069.04	36587.05
3 AGVs	32752.34	27331.57	25569.53	24719.54
4 AGVs	24692.5	20728.71	19133.09	18792.71
SR=SPT, SL=LFB, N=24				
MST	V2	V4	V6	V8
1 AGV	97970.48	81729.83	75871.19	73463.71
2 AGVs	49097.37	40748.81	38019.55	36702.83
3 AGVs	32919.19	27383.87	25608.27	24619.97
4 AGVs	24767	20652.64	19322.56	18709.36
SR=HPT, SL=LFB, N=24				
MST	V2	V4	V6	V8
1 AGVs	**98565.58**	81823.44	75989.38	72999.03
2 AGVs	49260.79	40945.79	38004.17	36685.11
3 AGVs	33042.55	27454.18	25678.5	24568.94
4 AGVs	25023.89	21331.56	20400.26	19820.9
SR=LCFS, SL=LFB, N=24				
MST	V2	V4	V6	V8
1 AGV	97879.09	81519.84	75881.95	73118.24
2 AGVs	49263.41	40928.2	37872.54	36838.19
3 AGVs	32796.56	27307.41	25464.87	24465.49
4 AGVs	24826.69	20626.72	19413.03	18781.82

Table 7.2: Percentage reduction in MST at different levels of AGVs and velocities

FCFS				
AGV	**V2**	**V4**	**V6**	**V8**
1 to 2	49.42628	50.02021	50.15823	49.77123
2 to 3	33.52984	33.05503	32.8338	32.43638
3 to 4	24.60843	24.15835	25.17229	23.97628
SPT				
AGV	**V2**	**V4**	**V6**	**V8**
1 to 2	49.88555	50.14206	49.88934	50.03951
2 to 3	32.95121	32.79835	32.64447	32.92079
3 to 4	24.76424	24.581	24.54565	24.00738
HPT				
AGV	**V2**	**V4**	**V6**	**V8**
1 to 2	50.02232	49.95837	49.98753	49.74576
2 to 3	32.92322	32.94993	32.4324	33.02748
3 to 4	24.26768	22.30121	20.5551	19.32536
LCFS				
AGV	**V2**	**V4**	**V6**	**V8**
1 to 2	49.66911	49.79357	50.09018	49.61833
2 to 3	33.42613	33.27973	32.76167	33.58661
3 to 4	24.30095	24.46474	23.76544	23.23136



(a) (b)

(c) (d)

Figure 7.5: Percentage reduction in MST at different levels of AGVs and velocities

It can also be seen from the table 7.2 and figure 7.5 that the decrease in MST is maximum i.e. about 50% when the number of AGV increases from one to two at all four velocities and four sequencing rules and then it reduces by about 32% when the system uses 3 AGVs instead of 2 AGVs. And further MST becomes about 24% less with the use of 4 AGVs. The same result is depicted in the figures 7.5 (a, b, c and d).

Table 7.3: Comparison of MST for different number and velocities of AGV under LFB for different sequencing rules

Number of AGVs	AGV velocity	V=600, N=24, SC=120; Performance measure: MST	
		Conditions	Sequencing rules
1AGV	V 2 m/s	Maximum	HPT
		Minimum	FCFS
	V 4 m/s	Maximum	HPT
		Minimum	LCFS
	V 6 m/s	Maximum	FCFS
		Minimum	SPT
	V 8 m/s	Maximum	SPT
		Minimum	FCFS
2AGVs	V 2 m/s	Maximum	FCFS
		Minimum	SPT
	V 4 m/s	Maximum	HPT
		Minimum	SPT
	V 6 m/s	Maximum	FCFS
		Minimum	LCFS
	V 8 m/s	Maximum	LCFS
		Minimum	FCFS
3AGVs	V 2 m/s	Maximum	HPT
		Minimum	FCFS
	V 4 m/s	Maximum	HPT
		Minimum	LCFS
	V 6 m/s	Maximum	HPT
		Minimum	LCFS
	V 8 m/s	Maximum	FCFS
		Minimum	LCFS
4AGVs	V 2 m/s	Maximum	HPT
		Minimum	FCFS
	V 4 m/s	Maximum	HPT
		Minimum	LCFS
	V 6 m/s	Maximum	HPT
		Minimum	FCFS
	V 8 m/s	Maximum	HPT
		Minimum	SPT

Table 7.3 shows the comparison of MST obtained for different sequencing rule and LFB system load conditions. The comparison is made for different number and velocities of AGV. It was observed from this table that for LFB system load conditions there is the affect of number and velocities on the MST performance of SFMS for different sequencing rule.

7.2.2. Effect of number of AGVs on WIP at different sequencing rules

In this section we find the effect of number of AGVs on work-in-process (WIP) at four different sequencing rules that are FCFS, SPT, HPT, and LCFS in stochastic environment. The figures 7.6, 7.7, 7.8 and 7.9 are drawn between WIP and number of AGVs at all four sequencing rules respectively. Figure 7.6 shows the graph between WIP and number of AGVs at different values of velocities. It is seen from the figure 7.6 that for FCFS sequencing rule and for 1 AGV, WIP is maximum for velocity 8 m/s and minimum for velocity 4 m/s. When AGV is increased to 2 WIP is maximum for velocity 2 m/s and minimum for 4 m/s. It is further observed that when AGV is increased to 3, WIP was maximum at velocity 2 m/s and it is minimum at 8 m/s. Finally when AGVs are increased to 4, WIP is maximum at velocity 2 m/s and minimum at 8 m/s.

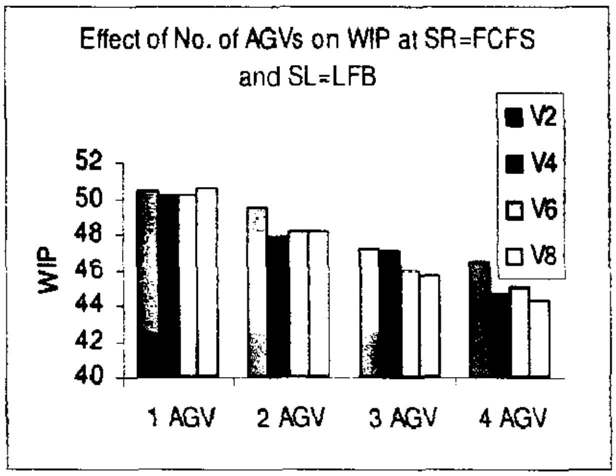


Figure 7.6: WIP performance at different levels of AGVs and velocities (V=600, N=24, SC=120, SR=FCFS, SL=LFB)

It is further observed from the figure 7.6 that the of WIP decreases with the increase in the number of AGVs in the system. Also WIP decreases with increase in velocities. This is because with increase in the number and velocities the parts are processed quickly hence reducing WIP.

Next sequencing rule is changed to SPT. Figure 7.7 shows the graph between WIP and number of AGVs at different values of velocities. It is seen from the figure 7.6 that for SPT sequencing rule and for 1 AGV, WIP is maximum for velocity 2 m/s and minimum for velocity 8 m/s. When AGV was increased to 2 WIP is maximum for velocity 2 m/s and minimum for 8 m/s. It was further observed that when AGV is increased to 3, WIP is maximum at velocity 2 m/s and it is minimum at 6 m/s. Finally when AGVs are increased to 4, WIP is maximum at velocity 2 m/s and minimum at 6 m/s. It was further observed from the figure 7.7 that the of WIP decreases with the increase in the number of AGVs in the system. Also WIP decreases with increase in velocities. This is because with increase in the number and velocities the parts are processed quickly hence reducing WIP.

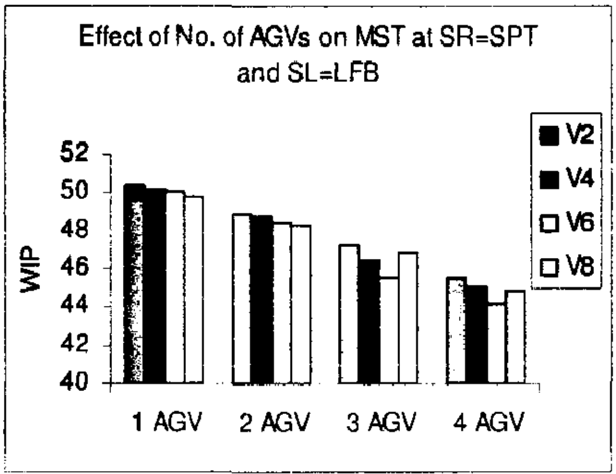


Figure 7.7: WIP performance at different levels of AGVs and velocities (V=600, N=24, SC=120, SR=SPT, SL=LFB)

Next sequencing rule was changed to HPT. Figure 7.8 shows the graph between WIP and number of AGVs at different values of velocities. It was seen from the figure 7.8 that for HPT sequencing rule and for 1 AGV, WIP is maximum for velocity 4 m/s and minimum for velocity 6 m/s. When AGV is increased to 2, WIP is maximum when AGV velocity is 2 m/s and minimum when velocity is 8 m/s. It is further observed that when AGV is increased to 3, WIP is maximum when the velocity is 2 m/s and it is minimum when the velocity is 8 m/s. Finally when AGVs are increased to 4, WIP is maximum at velocity 2 m/s and minimum at 4 m/s. It is further observed from the figure 7.8 that the of WIP decreases with the increase in the number of AGVs in the system. Also WIP decreases with increase in velocities. This is because with increase in the number and velocities the parts are processed quickly hence reducing WIP.

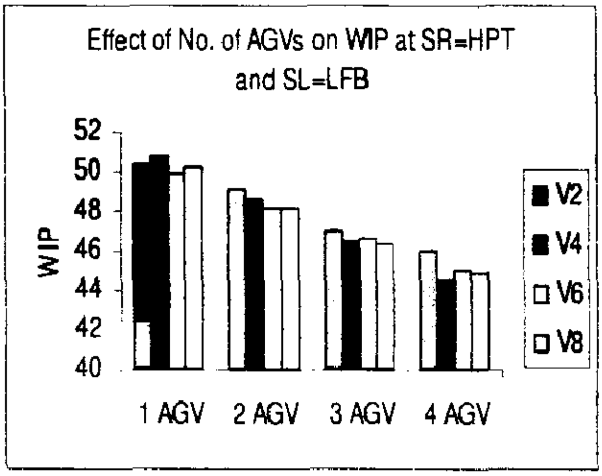


Figure 7.8: WIP performance at different levels of AGVs and velocities (V=600, N=24,SC=120, SR=HPT, SL=FBL)

Finally, sequencing rule was changed to LCFS. Figure 7.9 shows the graph between WIP and number of AGVs at different values of velocities. It is seen from the figure 7.9 that for LCFS sequencing rule and for all the different number of AGVs, WIP is maximum for velocity 8 m/s and minimum for velocity 2 m/s. Also WIP increases with increase in velocities and number of AGVs. This result is totally different than obtained with other sequencing rules namely FCFS, SPT and HPT.

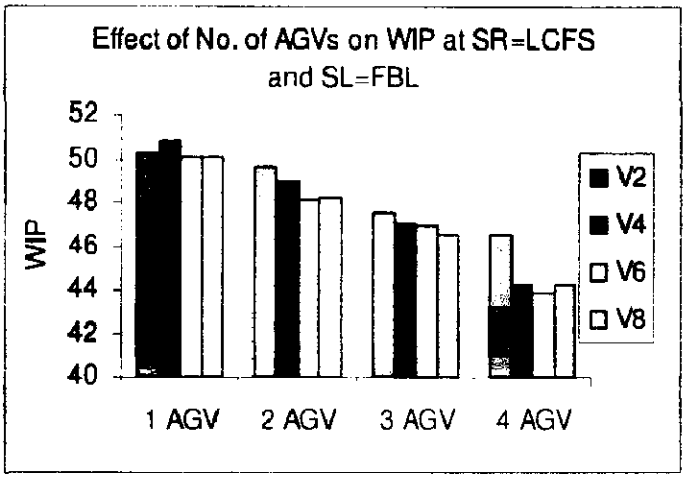


Figure 7.9: WIP performance at different levels of AGVs and velocities (V=600, N=24, SC=120, SR=LCFS, SL=LFB)

Table 7.4 shows the WIP for all combination of number of AGVs, velocities and sequencing rules.

Table 7.4: WIP performance at different levels of AGVs and velocities

SR=FCFS, SL=LFB, P=24				
WIP	V2	V4	V6	V8
1 AGV	50.44933	50.23167	50.168	50.61017
2 AGV	49.55167	47.81767	48.17033	48.18783
3 AGV	47.18217	47.06583	45.87867	45.741
4 AGV	46.4245	44.62217	45.0735	44.248
SR=SPT, SL=LFB, N=24				
WIP	V2	V4	V6	V8
1 AGV	50.36117	50.15217	50.034	49.76317
2 AGV	48.90617	48.75217	48.37817	48.27517
3 AGV	47.21333	46.42483	45.52533	46.7525
4 AGV	45.56233	45.0645	44.12117	44.86633
SR=HPT, SL=LFB, N=24				
WIP	V2	V4	V6	V8
1 AGV	50.40433	50.68833	49.90883	50.29667
2 AGV	49.08883	48.61	48.12567	48.09167
3 AGV	47.0005	46.456	46.569	46.3825
4 AGV	46.00083	44.46533	44.9775	44.935
SR=LCFS, SL=LFB, N=24				
WIP	V2	V4	V6	V8
1 AGV	50.24933	50.79933	50.07667	50.01433
2 AGV	49.62733	48.96933	48.10817	48.18683
3 AGV	47.53083	46.99817	46.873	46.467
4 AGV	46.4355	44.20083	43.84533	44.2255

It is evident from the above table that the value of WIP improves with the increase of AGVs at all the sequencing rules. The effect of velocity was seen more at higher number of AGVs in compression to the lower number of AGVs. It is also seen that the rate of improvement is almost uniform with the increase in number of AGVs.

Table 7.5: Comparison of WIP for different number and velocities of AGV under LFB for different sequencing rules

No. of AGVs	AGV velocity	V=600, N=24, SC=120; Performance measure: WIP	
		Conditions	Sequencing rules
1AGV	V 2 m/s	Maximum	FCFS
		Minimum	LCFS
	V 4 m/s	Maximum	LCFS
		Minimum	SPT
	V 6 m/s	Maximum	FCFS
		Minimum	HPT
	V 8 m/s	Maximum	FCFS
		Minimum	SPT
2AGV	V 2 m/s	Maximum	LCFS
		Minimum	SPT
	V 4 m/s	Maximum	LCFS
		Minimum	FCFS
	V 6 m/s	Maximum	SPT
		Minimum	LCFS
	V 8 m/s	Maximum	SPT
		Minimum	HPT
3AGV	V 2 m/s	Maximum	LCFS
		Minimum	HPT
	V 4 m/s	Maximum	FCFS
		Minimum	SPT
	V 6 m/s	Maximum	LCFS
		Minimum	SPT
	V 8 m/s	Maximum	SPT
		Minimum	FCFS
4AGV	V 2 m/s	Maximum	LCFS
		Minimum	SPT
	V 4 m/s	Maximum	SPT
		Minimum	LCFS
	V 6 m/s	Maximum	FCFS
		Minimum	LCFS
	V 8 m/s	Maximum	HPT
		Minimum	LCFS

Table 7.5 shows the comparison of WIP obtained for different sequencing rule and LFB system load conditions. The comparison is made for different number and velocities of AGV. It is observed from this table that for LFB system load conditions

there is the affect of number and velocities on the WIP performance of SFMS for different sequencing rule.

7.2.3. Effect of number of AGVs on RU at different sequencing rules

In this section we find the effect of number of AGVs on resource utilization (RU) at four different sequencing rules that are FCFS, SPT, HPT, and LCFS in stochastic environment. The figures 7.10, 7.11, 7.12 and 7.13 are drawn between RU and number of AGVs at all four sequencing rules respectively. Figure 7.10 shows the impact of number of AGVs at four sequencing rules for 600 parts at a system capacity 120 on the RU performance of the system. It is seen from the figure that with FCFS sequencing rule with different number of AGVs, RU is maximum at V8 that is velocity equal to 8 m /s and when 4 AGVS are used. Next the sequencing rule was changed to SPT.

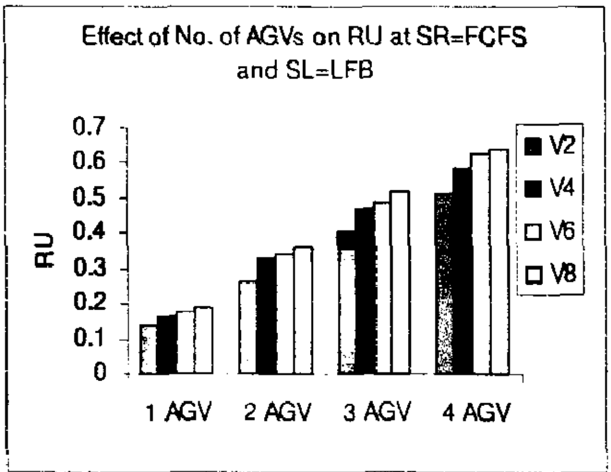


Figure 7.10: RU performance at different levels of AGVs and velocities (V=600, N=24, SC=120, SR=FCFS, SL=FBL)

Figure 7.11 shows the results. It is seen that for SPT rule also RU increases with increase in number of AGVs and velocities. It is observed that the maximum RU is obtained when 4 AGVs are used when operated at velocity of 8 m/s.

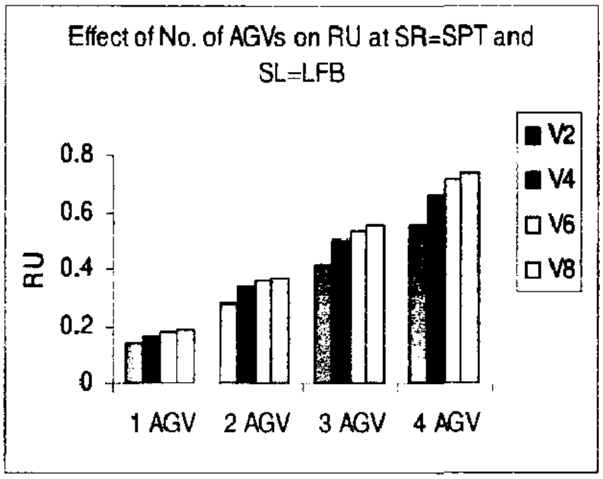


Figure 7.11: RU performance at different levels of AGVs and velocities (V=600, N=24, SC=120, SR=SPT, SL=FBL)

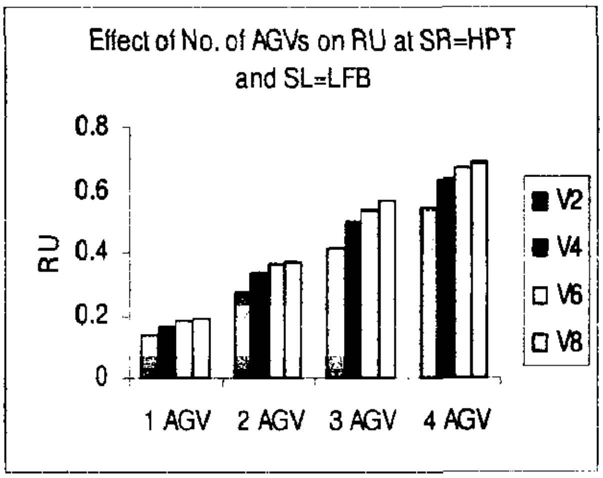


Figure 7.12: RU performance at different levels of AGVs and velocities (V=600, N=24, SC=120, SR=HPT, SL=FBL)

Now the system was operated with HPT and LCFS sequencing rules. It is observed that the performance of the system is similar to that obtained with SPT and FCFS sequencing rules (see Figure 7.12 and 7.13).

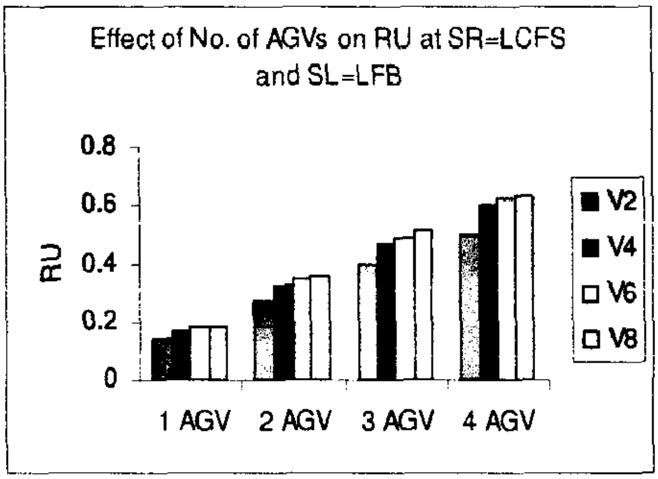


Figure 7.13: RU performance at different levels of AGVs and velocities (V=600, N=24, SC=120, SR=LCFS, SL=FBL)

Table 7.6 shows the RU for all combinations of AGVs, sequencing rules and velocities. It is also evident from the table that the effect of velocity is more prominent at higher number of AGVs while at lower numbers of AGV this effect is not very prominent.

Table 7.6: RU performance at different levels of AGVs and velocities

SR=FCFS, SL=LFB, P=24				
RU	V2	V4	V6	V8
1 AGV	0.142653	0.164398	0.175508	0.189053
2 AGV	0.263215	0.32598	0.340077	0.358655
3 AGV	0.403583	0.469525	0.486963	0.515303
4 AGV	0.513503	0.58647	0.627738	0.638322
SR=SPT, SL=LFB, N=24				
RU	V2	V4	V6	V8
1 AGV	0.140235	0.166958	0.181093	0.185558
2 AGV	0.280658	0.337848	0.359485	0.368517
3 AGV	0.414325	0.498985	0.530792	0.553007
4 AGV	0.555685	0.66135	0.716648	0.733915
SR=HPT, SL=LFB, N=24				
RU	V2	V4	V6	V8
1 AGV	0.138185	0.166448	0.180317	0.188933
2 AGV	0.275427	0.331552	0.359473	0.372575
3 AGV	0.412182	0.499392	0.536075	0.565017
4 AGV	0.543833	0.634533	0.67331	0.683552
SR=LCFS, SL=LFB, N=24				
RU	V2	V4	V6	V8
1 AGV	0.139092	0.16645	0.180327	0.185182
2 AGV	0.266372	0.324747	0.349117	0.353642
3 AGV	0.39854	0.46867	0.494637	0.514655
4 AGV	0.500695	0.598568	0.626065	0.631737

Table 7.7 shows the comparison of RU obtained for different sequencing rule and LFB system load conditions. The comparison is made for different number and velocities of AGV. It is observed from this table that for LFB system load conditions there is the affect of number and velocities on the MST performance of SFMS for different sequencing rule.

Table 7.7: Comparison of RU for different number and velocities of AGV under LFB for different sequencing rules

No. of AGVs	AGV velocity	V=600, N=24, SC=120; Performance measure: RU	
		Conditions	Sequencing rules
1AGV	V2	Maximum	FCFS
		Minimum	HPT
	V4	Maximum	SPT
		Minimum	FCFS
	V6	Maximum	SPT
		Minimum	FCFS
	V8	Maximum	FCFS
		Minimum	LCFS
2AGV	V2	Maximum	SPT
		Minimum	FCFS
	V4	Maximum	SPT
		Minimum	LCFS
	V6	Maximum	SPT
		Minimum	FCFS
	V8	Maximum	HPT
		Minimum	LCFS
3AGV	V2	Maximum	SPT
		Minimum	LCFS
	V4	Maximum	HPT
		Minimum	LCFS
	V6	Maximum	HPT
		Minimum	FCFS
	V8	Maximum	HPT
		Minimum	LCFS
4AGV	V2	Maximum	SPT
		Minimum	LCFS
	V4	Maximum	SPT
		Minimum	FCFS
	V6	Maximum	SPT
		Minimum	LCFS
	V8	Maximum	SPT
		Minimum	LCFS

7.2.4. Effect of AGV velocity on MST at different sequencing rules

In this section we find the effect of AGV velocity on makespan at four different sequencing rules that are FCFS, SPT, HPT, and LCFS in stochastic environment. The figures 7.14 (a, b, c, and d) are drawn between makespan and AGV velocity at all four sequencing rules respectively.

Figure 7.14 shows the impact of AGV velocity at four sequencing rules for 600 parts at a system capacity 120 on the MST performance of the system. It is seen from the figure that at V2, MST is maximum for 1AGV at HPT and minimum for 4AGV at FCFS. At V4, MST is maximum for 1AGV at HPT and minimum for 4AGV at LCFS. At V6, MST is maximum for 1AGV at FCFS and minimum for 4AGV at FCFS. Similarly at V8 it is observed that MST is maximum for 1AGV at SPT and minimum for 4AGV at SPT. Further it is observed from the figure that the valve of MST decreases with the increase of the AGV velocity in the system in all the combinations. One of the important observations made from the figure is that the decrease in the MST is more significant when the system uses two AGVs instead of one AGV. The sequencing rules are not having any significant effect on the MST performance of the system. Table 7.8 shows the MST as obtained for MST performance at different levels of velocities, AGV fleet and sequencing rules. Similarly table 7.9 shows the percentage reduction in MST with change of velocity with sequencing rules. It can also be seen from the table 7.9 that the reduction in MST is about 16% when the AGV velocity increases from 2 m/s to 4 m/s with all four sequencing rules and then it further improved by about 6% when the velocity of AGV is increased from 4 m/s to 6 m/s. when the velocity of AGV is further increased from 6 m/s to 8 m/s AGV there is further 3% reduction in the MST. The same results are depicted in figure 7.15.

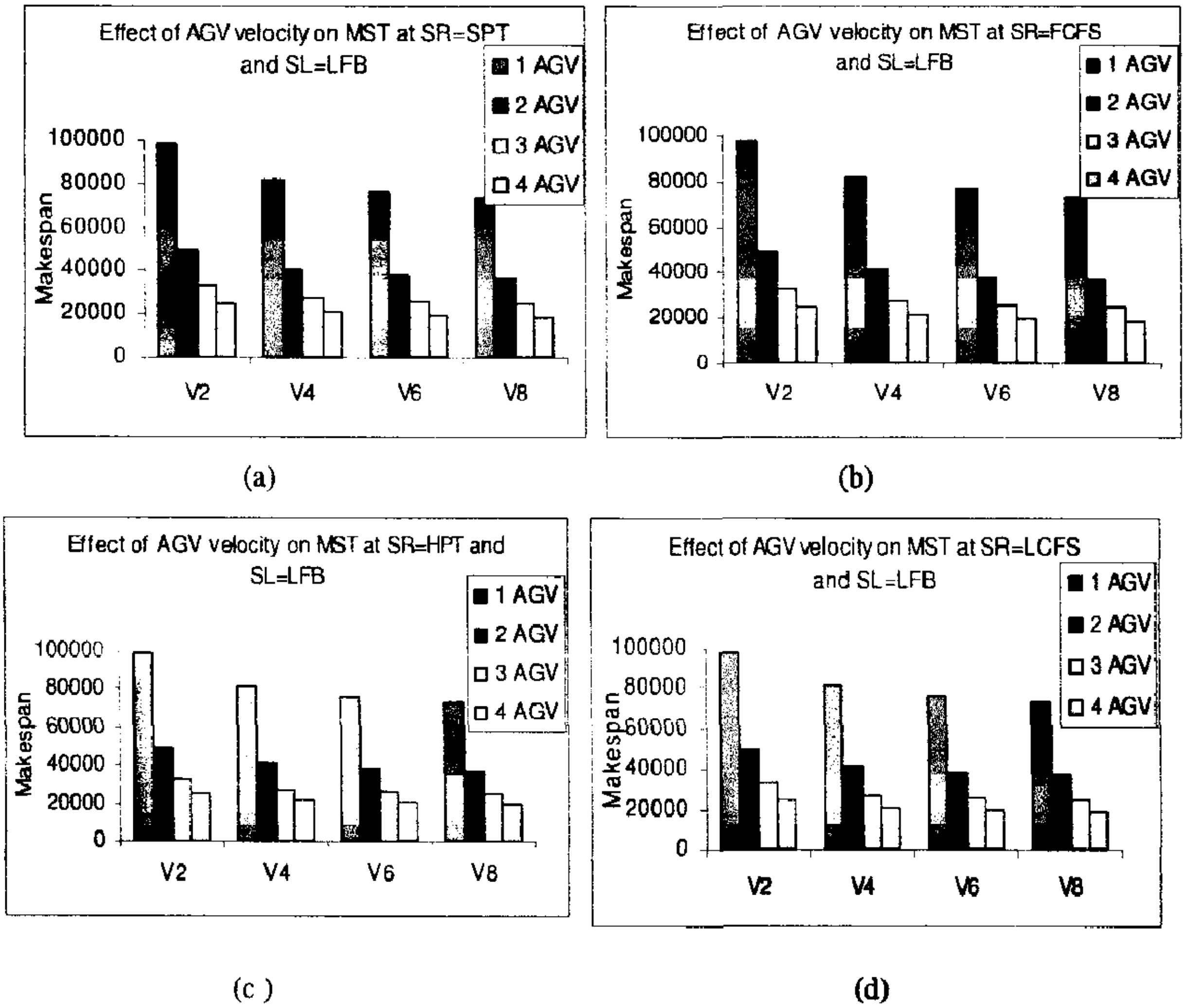


Figure 7.14: MST performance at different levels of velocities, AGV fleet and sequencing rules

Table 7.8: MST performance at different levels of velocities, AGV fleet and sequencing rules

SR=FCFS, SL=LFB, N=24				
MST	V2	V4	V6	V8
1 AGV	97429.53	81686.85	76379.79	72840.83
2 AGV	49273.74	40826.92	38069.04	36587.05
3 AGV	32752.34	27331.57	25569.53	24719.54
4 AGV	24692.5	20728.71	19133.09	18792.71
SR=SPT, SL=LFB, N=24				
MST	V2	V4	V6	V8
1 AGV	97970.48	81729.83	75871.19	73463.71
2 AGV	49097.37	40748.81	38019.55	36702.83
3 AGV	32919.19	27383.87	25608.27	24619.97
4 AGV	24767	20652.64	19322.56	18709.36
SR=HPT, SL=LFB, N=24				
MST	V2	V4	V6	V8
1 AGV	98565.58	81823.44	75989.38	72999.03
2 AGV	49260.79	40945.79	38004.17	36685.11
3 AGV	33042.55	27454.18	25678.5	24568.94
4 AGV	25023.89	21331.56	20400.26	19820.9
SR=LCFS, SL=LFB, N=24				
MST	V2	V4	V6	V8
1 AGV	97879.09	81519.84	75881.95	73118.24
2 AGV	49263.41	40928.2	37872.54	36838.19
3 AGV	32796.56	27307.41	25464.87	24465.49
4 AGV	24826.69	20626.72	19413.03	18781.82

Table 7.9: Percentage reduction in MST with change of velocity for different sequencing rules

SR=FCFS				SR=HPT			
Vel.	2 to 4	4 to 6	6 to 8	Vel.	2 to 4	4 to 6	6 to 8
1 AGV	16.15802	6.496828	4.633379	1 AGV	16.98578	7.130058	3.935226
2 AGV	17.14265	6.75505	3.892882	2 AGV	16.87956	7.184174	3.470838
3 AGV	16.55079	6.446906	3.324226	3 AGV	16.91266	6.46777	4.320994
4 AGV	16.05261	7.69764	1.779009	4 AGV	14.75521	4.365836	2.839963
SR=SPT				SR=LCFS			
Vel.	2 to 4	4 to 6	6 to 8	Vel.	2 to 4	4 to 6	6 to 8
1 AGV	16.57708	7.168294	3.173125	1 AGV	16.71373	6.915977	3.64211
2 AGV	17.00408	6.697763	3.463286	2 AGV	16.91968	7.465895	2.731144
3 AGV	16.81486	6.484109	3.859325	3 AGV	16.73698	6.747401	3.924531
4 AGV	16.61226	6.440279	3.173489	4 AGV	16.91715	5.884067	3.251456

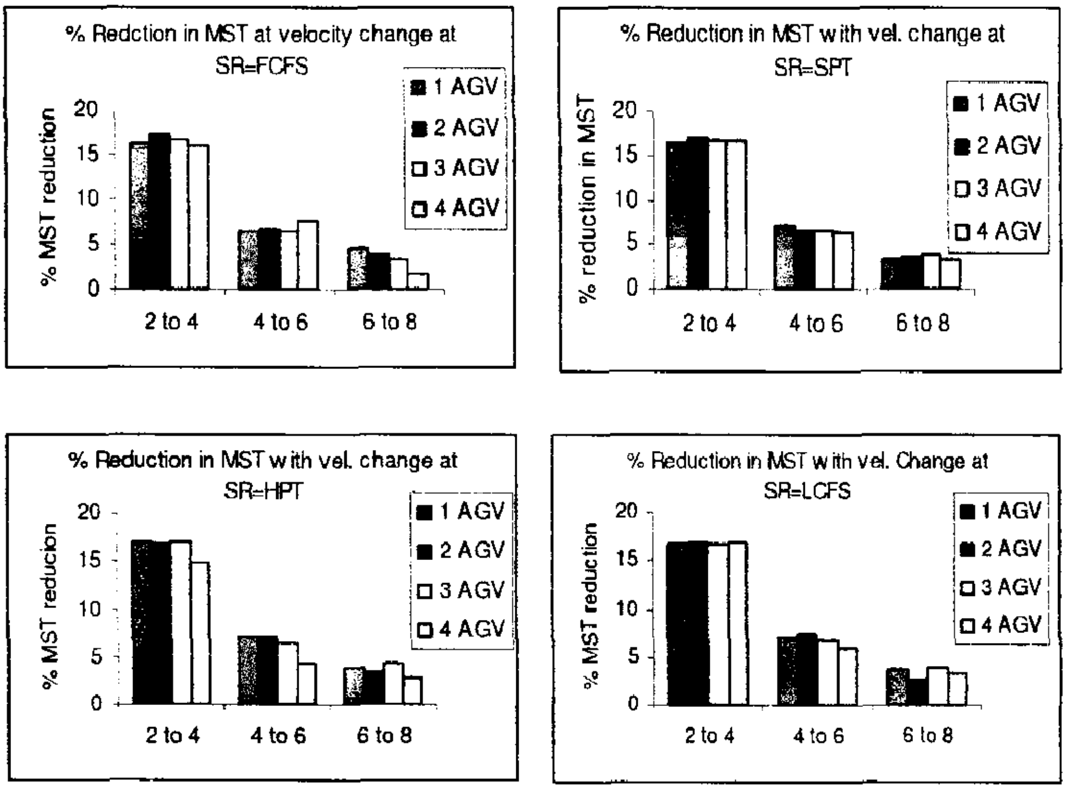


Figure 7.15: Percentage reduction in MST at change in velocity for different sequencing rules

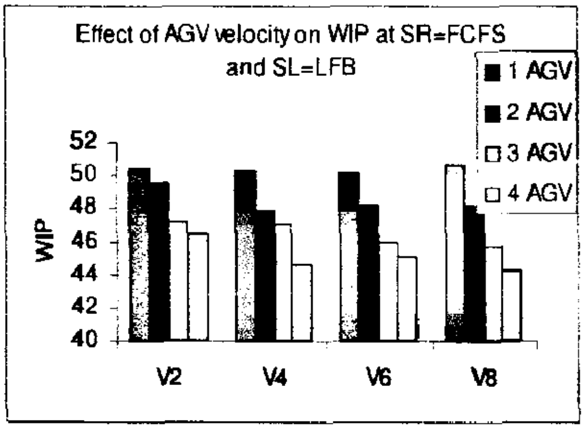
Table 7.10 shows the comparison of MST obtained for different sequencing rule and LFB system load conditions. The comparison is made for different velocities number and of AGV. It is observed from this table that for LFB system load conditions there is the affect of number and velocities on the MST performance of SFMS for different sequencing rule.

Table 7.10: Comparison of MST for different velocities and number of AGV under LFB for different sequencing rules

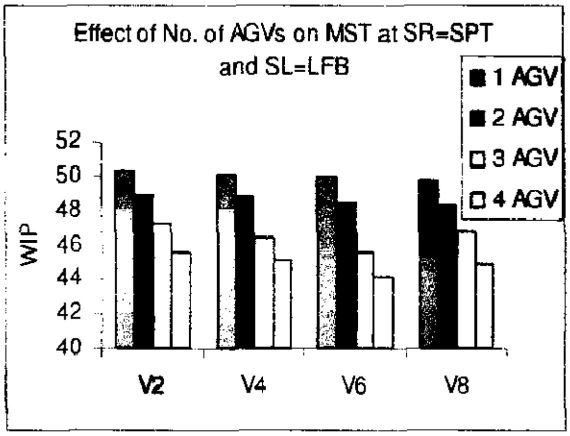
AGV Velocity m/s	No. of AGVs	V=600, N=24, SC=120; Performance measure: MST	
		Conditions	Sequencing rules
V2	1AGV	Maximum	HPT
		Minimum	FCFS
	2AGV	Maximum	FCFS
		Minimum	SPT
	3AGV	Maximum	HPT
		Minimum	FCFS
	4AGV	Maximum	HPT
		Minimum	FCFS
V4	1AGV	Maximum	HPT
		Minimum	LCFS
	2AGV	Maximum	HPT
		Minimum	SPT
	3AGV	Maximum	HPT
		Minimum	LCFS
	4AGV	Maximum	HPT
		Minimum	LCFS
V6	1AGV	Maximum	FCFS
		Minimum	SPT
	2AGV	Maximum	FCFS
		Minimum	LCFS
	3AGV	Maximum	HPT
		Minimum	LCFS
	4AGV	Maximum	HPT
		Minimum	FCFS
V8	1AGV	Maximum	SPT
		Minimum	FCFS
	2AGV	Maximum	LCFS
		Minimum	FCFS
	3AGV	Maximum	FCFS
		Minimum	LCFS
	4AGV	Maximum	HPT
		Minimum	SPT

7.2.5. Effect of AGV velocity on WIP at different sequencing rules

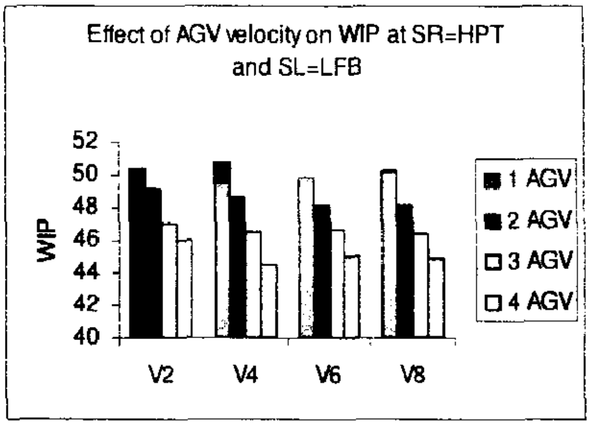
In this section we find the effect of AGV velocity on WIP at four different sequencing rules that are FCFS, SPT, HPT, and LCFS in stochastic environment. The figures 7.16 (a, b, c, and d) are drawn between WIP and number of AGVs at all four sequencing rules respectively. It can be seen from the figure 7.16 that the effect of velocity on WIP is not very much visible with the use of one AGV in the system but as we increased the number of AGVs in the system the effect of velocity become visible on the WIP.



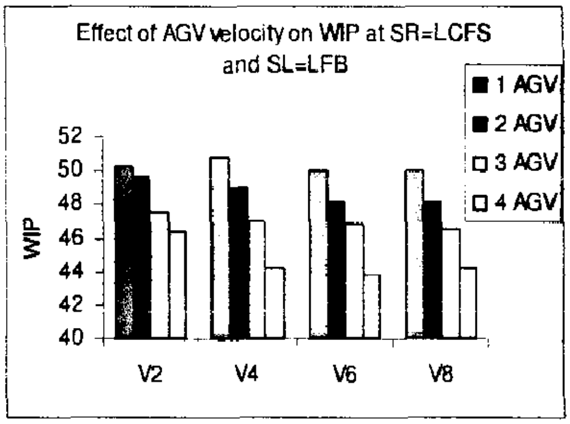
(a)



(b)



(c)



(d)

Figure 7.16: WIP performance at different levels of velocities, AGV fleet and sequencing rules

In figure 7.13 there is a significant reduction in the value of WIP when the velocity increases from V2 to V4 at all sequencing rules except at SPT and then it increases in case of FCFS and HPT.

Table 7.11: Comparison of WIP for different velocities and number of AGV under LFB for different sequencing rules

AGV Velocity m/s	No. of AGVs	V=600, N=24, SC=120; Performance measure: WIP	
		Conditions	Sequencing rules
V2	1AGV	Maximum	FCFS
		Minimum	LCFS
	2AGV	Maximum	LCFS
		Minimum	SPT
	3AGV	Maximum	FCFS
		Minimum	HPT
	4AGV	Maximum	LCFS
		Minimum	HPT
V4	1AGV	Maximum	LCFS
		Minimum	SPT
	2AGV	Maximum	LCFS
		Minimum	FCFS
	3AGV	Maximum	FCFS
		Minimum	SPT
	4AGV	Maximum	SPT
		Minimum	LCFS
V6	1AGV	Maximum	FCFS
		Minimum	HPT
	2AGV	Maximum	SPT
		Minimum	LCFS
	3AGV	Maximum	LCFS
		Minimum	SPT
	4AGV	Maximum	FCFS
		Minimum	LCFS
V8	1AGV	Maximum	FCFS
		Minimum	SPT
	2AGV	Maximum	SPT
		Minimum	HPT
	3AGV	Maximum	SPT
		Minimum	FCFS
	4AGV	Maximum	HPT
		Minimum	LCFS

Table 7.11 shows the comparison of WIP obtained for different sequencing rule and LFB system load conditions. The comparison is made for different velocities and number and of AGV. It is observed from this table that for LFB system load conditions there is the affect of number and velocities on the MST performance of SFMS for different sequencing rule.

7.2.6. Effect of AGV velocity on RU at different sequencing rules

In this section we found the effect of AGV velocity on RU at four different sequencing rules that are FCFS, SPT, HPT, and LCFS in stochastic environment. The figures 7.17 (a, b, c, and d) are drawn between RU and number of AGVs at all four sequencing rules respectively. It is found from the figure 7.17 that the value of RU is increased by the increase of velocity at all sequencing rules. It is also evident from the figure that the effect of velocity is having a significant effect with larger number of AGVs used i.e. 4 AGV while at lower number of AGVs has a little effect on the value of RU at all sequencing rules.

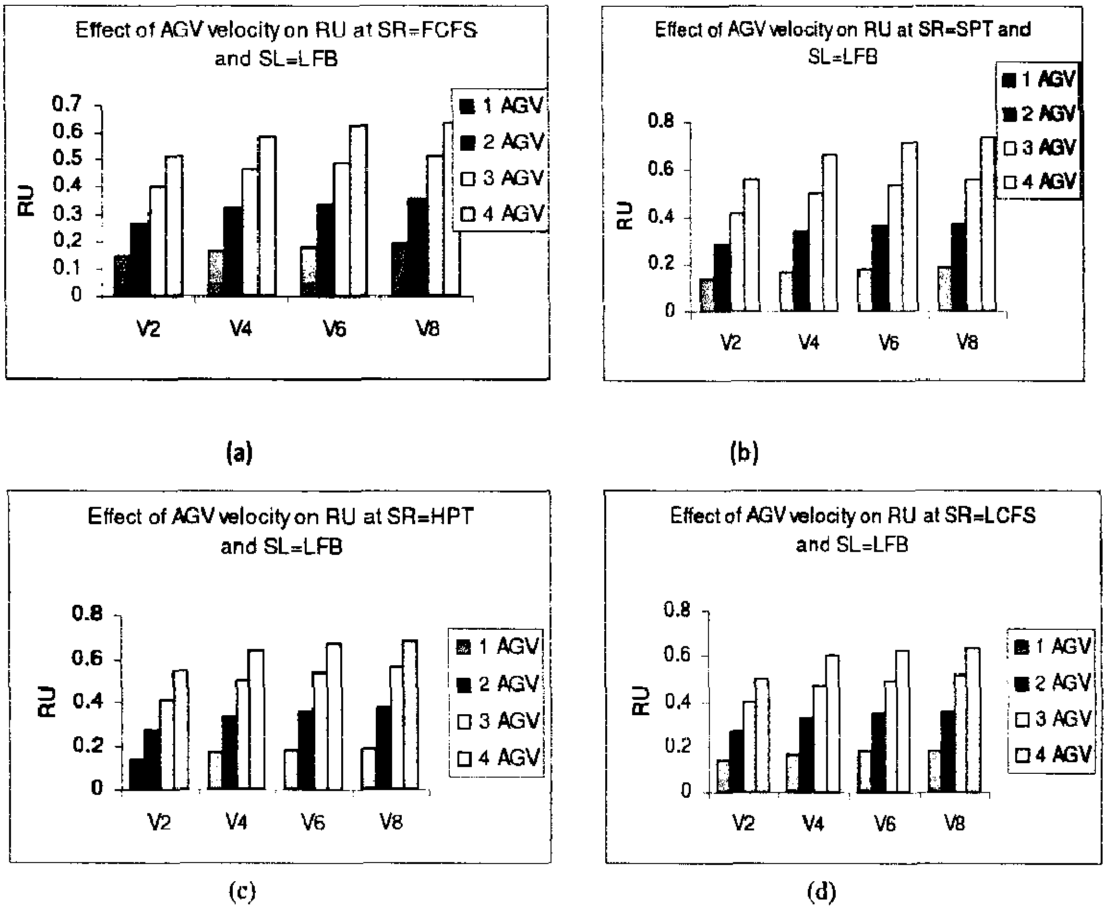


Figure 7.17: RU performance at different levels of velocities, AGV fleet and sequencing rules

Table 7.12: Comparison of RU for different velocities and number of AGV under LFB for different sequencing rules

AGV Velocity m/s	No. of AGVs	V=600, N=24, SC=120; Performance measure: RU	
		Conditions	Sequencing rules
V2	1AGV	Maximum	FCFS
		Minimum	HPT
	2AGV	Maximum	SPT
		Minimum	FCFS
	3AGV	Maximum	SPT
		Minimum	LCFS
	4AGV	Maximum	SPT
		Minimum	LCFS
V4	1AGV	Maximum	SPT
		Minimum	FCFS
	2AGV	Maximum	SPT
		Minimum	LCFS
	3AGV	Maximum	HPT
		Minimum	LCFS
	4AGV	Maximum	SPT
		Minimum	FCFS
V6	1AGV	Maximum	SPT
		Minimum	FCFS
	2AGV	Maximum	SPT
		Minimum	FCFS
	3AGV	Maximum	HPT
		Minimum	FCFS
	4AGV	Maximum	SPT
		Minimum	LCFS
V8	1AGV	Maximum	FCFS
		Minimum	LCFS
	2AGV	Maximum	HPT
		Minimum	LCFS
	3AGV	Maximum	HPT
		Minimum	LCFS
	4AGV	Maximum	SPT
		Minimum	LCFS

Table 7.12 shows the comparison of RU obtained for different sequencing rule and LFB system load conditions. The comparison is made for different velocities and number and of AGV. It is observed from this table that for LFB system load conditions there is the affect of number and velocities on the MST performance of SFMS for different sequencing rule.

7.3 Conclusion

In this chapter, the simulation experiments were carried out with four sequencing rules (i.e. FCFS, SPT, HPT, and LCFS) at four levels of AGV fleet (i.e. 1 AGV, 2 AGV, 3 AGV and 4 AGVs) and at four AGV velocities (i.e. 2 m/s, 4 m/s, 6 m/s and 8 m/s). The performance of the system was measured by three performance measures such as MST, WIP and resource utilization. It was observed from series of experiments that performance was improved with the increase of number of AGVs in all of the combinations of factors. It was also observed that increase in the performance is more when 2 AGVs are used instead of 1 AGV. From the above discussion it is seen that the AGV velocity has an impact on the performance measures but this effect is more visible at higher number of AGVs in compare to the lower number of AGVs. There was effect of sequencing rules for different combinations of number of AGVs and velocities.

Chapter 8

Performance of SFMS under Sequencing and Routing Flexibility

8.1 Introduction

In the previous chapters we study the impact of different design, planning and control decisions on the performance of SFMS individually. The systems were differentiated on the basis of two manufacturing flexibilities. These are sequencing flexibility and routing flexibility. The previous result shows that the sequencing flexibility level 4 i.e. SF3 perform best among all the four sequencing flexibility levels. When the system is operated with routing flexibility, the maximum gain is achieved when the system moves from routing flexibility level one i.e. RF0 to routing flexibility level 2 i.e. RF1. In this chapter we study the combined effect of sequencing flexibility (SF3) and routing flexibility (RF1) on the performance of SFMS under different scenarios. Three performance measures are considered for the study of SFMS i.e. MST, WIP and RU. The different load conditions for the various set of performance measures are LUB, LFB, LBMUPT and LUMBPT. Control decisions are exploited in eth form of sequencing rules. These sequencing rules are FCFS, SPT, HPT and LCFS. The experiments are carried out for the said four load conditions and sequencing rules under stochastic environment.

8.2 Simulation results and discussion

In this section we compare the performance of SFMS under sequencing flexibility, routing flexibility and combination of sequencing and routing flexibility. The study is carried out to find the effect of the above options on the MST, WIP and RU performance measures of SFMS as shown in figure 8.0.

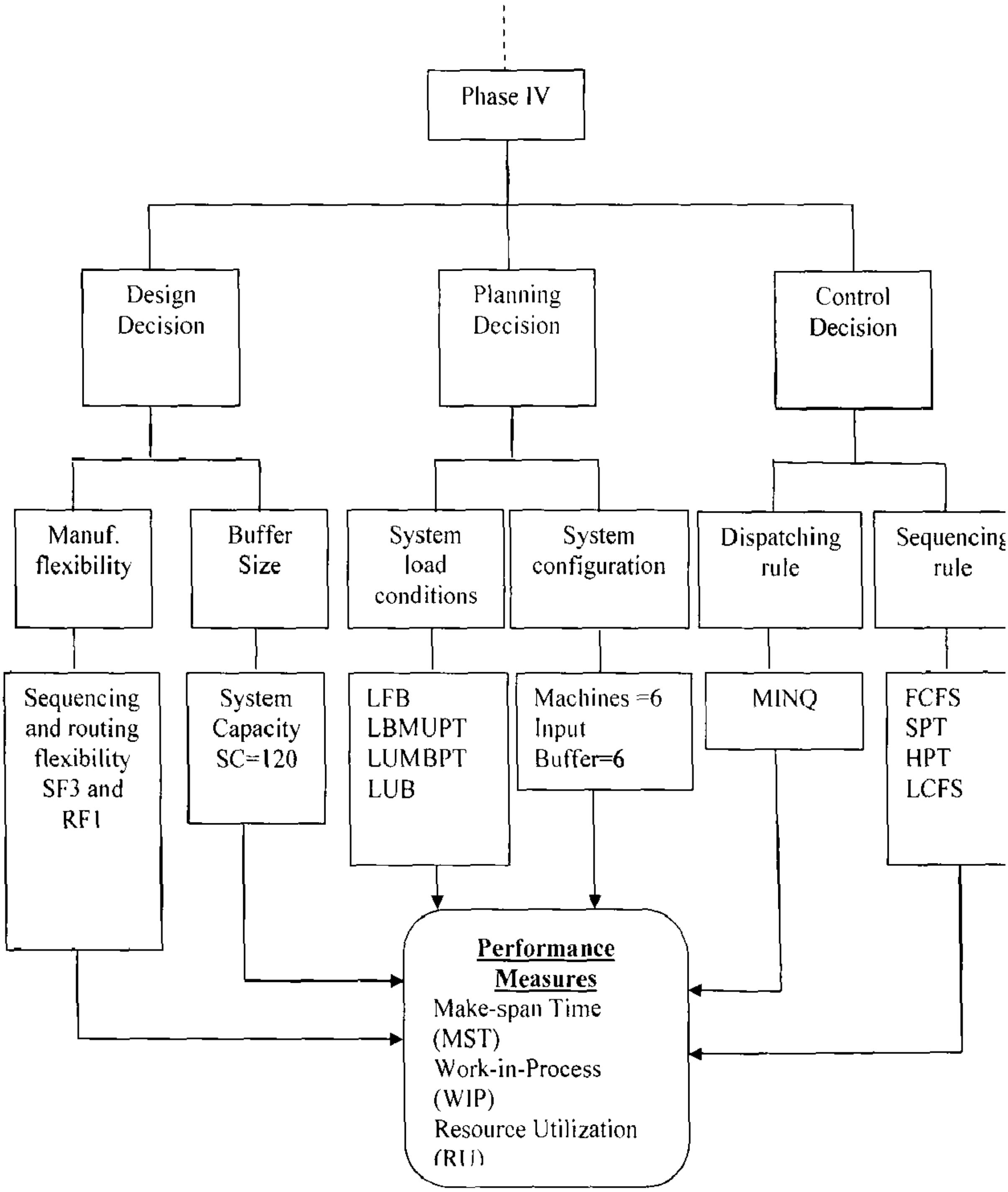


Figure 8.0: Salient Features of the Study of Phase IV

8.2.1. Combine Effect of SF and RF on MST at different load conditions

In this section we find the combined effect of sequencing and routing flexibility on make-span time (MST) at different system load conditions. Figures 8.1 to 8.4 are drawn between MST and combined model at all four system load conditions. Tables 8.1 to 8.4 shows the MST value at SF3, RF1 and combined model under four system load conditions and four sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively. Table 8.1(a) shows the combined effect of sequencing and routing flexibility on MST at LUB with sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively. Table 8.1(b) shows the percentage decrease in MST with three combinations (i.e. percentage decrease from RF1 to SF3RF1, SF3 to RF1 and SF3 to SF3RF1). It is seen from this table and figure 8.1 that the maximum percentage decrease in the MST is achieved when we switch the system from pure sequencing flexibility to the combined model of sequencing and routing flexibility (i.e. SF3-SF3RF1). The percentage decrease in MST is maximum at SF3-SF3RF1 with sequencing rule HPT and minimum at RF1-SF3RF1 with sequencing rule SPT.

Table 8.1: MST with different sequencing rule at LUB

MST at LUB			
	SF3	RF1	SF3RF1
FCFS	16734.6797	14480.10187	13743.2361
SPT	16709.6207	14244.42733	13883.7866
HPT	17320.5315	15143.37653	13925.5907
LCFS	16980.0541	14560.61507	14108.1195

(a)

Percentage decrease of MST at LUB			
	RF1-SF3RF1	SF3-RF1	SF3-SF3RF1
FCFS	5.36166127	15.57017914	21.76666067
SPT	2.59756753	17.30637071	20.35348291
HPT	8.74494921	14.37694556	24.37915135
LCFS	3.20734147	16.61632462	20.35660836

(b)

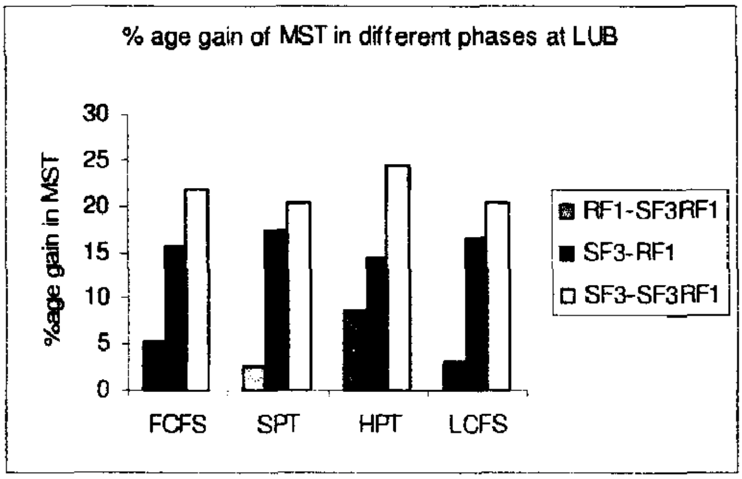


Figure 8.1: Percentage decrease of MST with LUB

Table 8.2(a) shows the combine effect of sequencing and routing flexibility on MST at LFB with sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively. It is seen from the table that MST is maximum at all sequencing rules with sequencing flexibility and minimum at all sequencing rules with the combined sequencing and routing flexibility SFMS. Table 8.2(b) shows the percentage improvement in MST with three combinations (i.e. percentage decrease from RF1 to SF3RF1, SF3 to RF1 and SF3 to SF3RF1).

Table 8.2: MST with different sequencing rule at LFB

MST at LFB			
	SF3	**RF1**	**SF3RF1**
FCFS	16530.82233	14201.3796	13664.0248
SPT	16542.0072	14129.0111	13786.9719
HPT	16801.264	14575.8543	13812.5882
LCFS	16681.5552	14339.2101	13960.8813

(a)

Percentage decrease of MST at LFB			
	RF1-SF3RF1	**SF3-RF1**	**SF3-SF3RF1**
FCFS	3.932624595	16.4029327	20.98062303
SPT	2.480887288	17.0783082	19.98288906
HPT	5.525873372	15.267782	21.63733369
LCFS	2.709920373	16.3352453	19.48783778

(b)

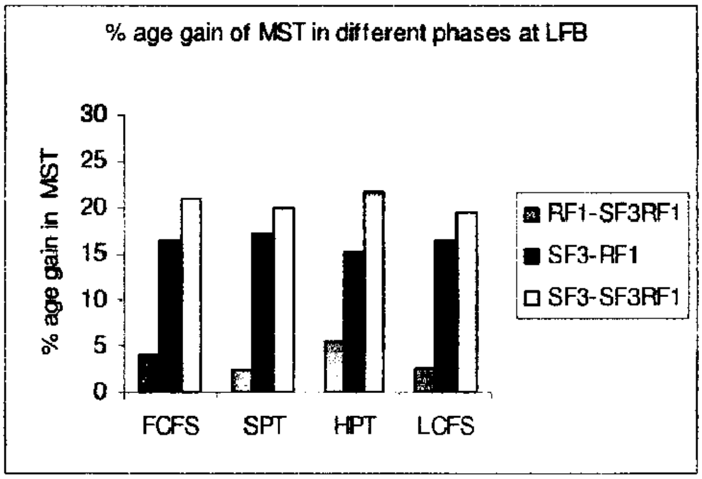


Figure 8.2: Percentage decrease of MST with LFB

It is seen from the figure 8.2 that the maximum percentage decrease in the MST is achieved when we switch the system from pure sequencing flexibility to the combined model of sequencing and routing flexibility (i.e. SF3-SF3RF1). The percentage decrease in MST is maximum at SF3-SF3RF1 with sequencing rule HPT and minimum at RF1-SF3RF1 with sequencing rule SPT.

The Table 8.3(a) shows the combine effect of sequencing and routing flexibility on MST at LBMUPT with sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively. It is seen from the table that MST is maximum at all sequencing rules with sequencing flexibility and minimum at all sequencing rules with the combined model. Table 8.3(b) shows the percentage decrease in MST with three combinations (i.e. percentage decrease from RF1 to SF3RF1, SF3 to RF1 and SF3 to SF3RF1). It is seen from the figure 8.3 that the maximum percentage decrease in the MST is achieved when we switch the system from pure sequencing flexibility to the combined model of sequencing and routing flexibility (i.e. SF3-SF3RF1). The percentage decrease in MST is maximum at SF3-SF3RF1 with sequencing rule HPT and minimum at RF1-SF3RF1 with sequencing rule LCFS.

Table 8.3: MST with different sequencing rule at LBMUPT

MST at LBMUPT			
	SF3	RF1	SF3RF1
FCFS	16760.00107	14177.6223	13734.6696
SPT	16848.96667	14118.7647	13771.3275
HPT	17327.0116	14600.2107	13783.1135
LCFS	16952.21513	14265.4688	13952.378

(a)

Percentage decrease of MST at LBMUPT			
	RF1-SF3RF1	SF3-RF1	SF3-SF3RF1
FCFS	3.225069693	18.2144703	22.02696938
SPT	2.522902991	19.3373994	22.34816627
HPT	5.928248602	18.6764487	25.7118836
LCFS	2.24399597	18.8339155	21.50054373

(b)

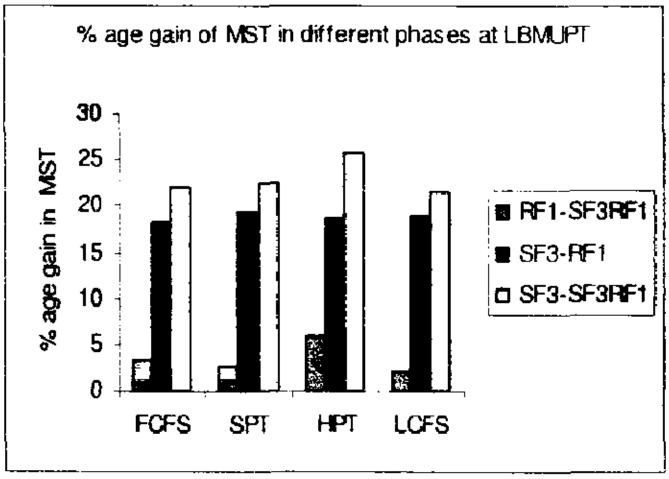


Figure 8.3: Percentage decrease of MST with LBMUPT

The Table 8.4(a) shows the combine effect of sequencing and routing flexibility on MST at LUMBPT with sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively. It is seen from the figure that MST is maximum at all sequencing rules with sequencing flexibility and minimum at all sequencing rules with the combined model. Table 8.4(b) shows the percentage decrease in MST with three combinations (i.e. percentage decrease from RF1 to SF3RF1, SF3 to RF1 and SF3 to SF3RF1). It is seen from the figure 8.4 that the maximum percentage decrease in the MST is achieved when we switch the system from pure sequencing flexibility to the combined model of sequencing and routing flexibility (i.e. SF3-SF3RF1). The percentage gain in MST is maximum at SF3-SF3RF1 with sequencing rule HPT and minimum at RF1-SF3RF1 with sequencing rule LCFS.

Table 8.4: MST with rule different sequencing at LUMBPT

MST at LUMBPT			
	SF3	**RF1**	**LUMBPT**
FCFS	16534.93113	14208.57193	13672.5734
SPT	16526.6714	14142.74887	13784.5215
HPT	16738.34027	14513.0268	13783.1135
LCFS	16689.43967	14308.5932	13952.378

(a)

Percentage gain of MST at LUMBPT			
	RF1-SF3RF1	**SF3-RF1**	**SF3-SF3RF1**
FCFS	3.920246157	16.37292763	20.93503285
SPT	2.598765337	16.85614696	19.892964
HPT	5.295706953	15.33321407	21.4409231
LCFS	2.553078765	16.63927707	19.61716968

(b)

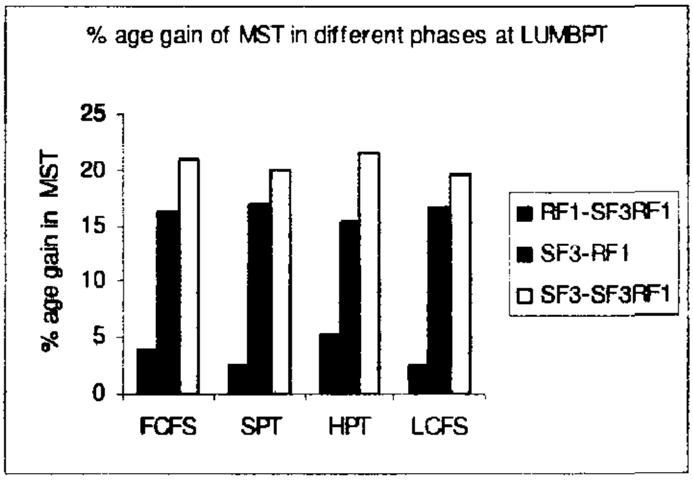


Figure 8.4: Percentage decrease of MST with LUMBPT

8.2.2. Combine Effect of SF and RF on WIP at different load conditions

In this section we find the combined effect of sequencing and routing flexibility on work-in-process (WIP) at different system load conditions. The figures 8.5 to 8.8 are drawn between WIP and combined model at all four system load conditions. Tables 8.5

to 8.8 shows the value of WIP at SF3, RF1 and combined model under four system load conditions and four sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively.

Table 8.5(a) shows the combine effect of sequencing and routing flexibility on WIP at LUB with sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively. It is seen from the figure that WIP is maximum at all sequencing rules with sequencing flexibility and minimum at all sequencing rules with RF1. Table 8.1(b) shows the percentage increase/decrease in WIP with three combinations (i.e. percentage increase/decrease from RF1 to SF3RF1, SF3 to RF1 and SF3 to SF3RF1). It is seen from the figure 8.5 that the maximum percentage decrease in the WIP is achieved when we switch the system from pure sequencing flexibility to routing flexibility (i.e. SF3-RF1). At this condition of the system the percentage decrease in WIP is maximum at SF3 with sequencing rule HPT and minimum with sequencing rule LCFS. The performance of the system deteriorates with RF1-SF3RFI for all sequencing rules. There is marginal decrease in WIP with SF3-SF3RF1 system for all sequencing rules.

Table 8.5: WIP with different sequencing rule at LUB

WIP at LUB			
	SF3	**RF1**	**SF3RF1**
FCFS	58.00816667	41.076667	55.95033333
SPT	55.34366667	40.6435	54.58833333
HPT	59.59483333	41.802167	58.9275
LCFS	56.49016667	40.008333	52.97316667

(a)

Percentage increase/decrease of WIP at LUB			
	RF1-SF3RF1	**SF3-RF1**	**SF3-SF3RF1**
FCFS	-26.58369625	41.219265	3.677964385
SPT	-25.54544622	36.168555	1.383690044
HPT	-29.06170011	42.563982	1.132465035
LCFS	-24.47434078	41.196001	6.639210418

(b)

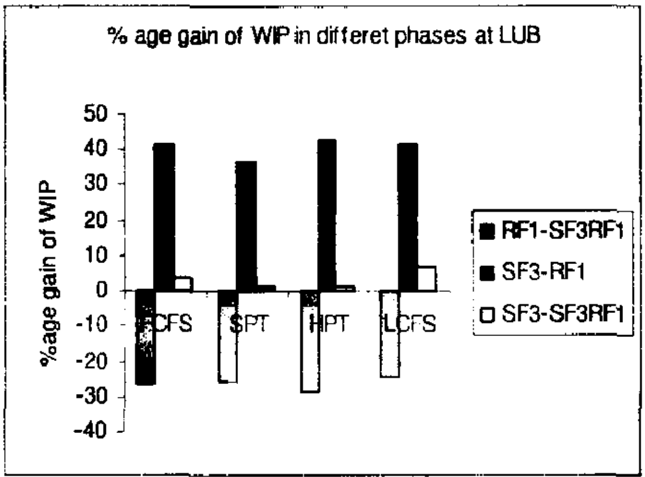


Figure 8.5: Percentage increase/decrease of WIP with LUB

Table 8.6(a) shows the combined effect of sequencing and routing flexibility on WIP at LFB with sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively. It is seen from the figure that WIP is maximum at all sequencing rules with sequencing flexibility and minimum at all sequencing rules with RF1.

Table 8.6: WIP with different sequencing rule at LFB

WIP LFB			
	SF3	**RF1**	**SF3RF1**
FCFS	58.22883333	41.56033333	56.769
SPT	55.4545	40.32033333	53.90316667
HPT	58.30633333	41.8705	56.4655
LCFS	53.90783333	41.51316667	52.37133333

(a)

Percentage increase/decrease of WIP at LFB			
	RF1-SF3RF1	**SF3-RF1**	**SF3-SF3RF1**
FCFS	-26.79044314	40.10675243	2.571532585
SPT	-25.19858141	37.53482527	2.878000365
HPT	-25.84764148	39.25396958	3.260102777
LCFS	-20.73303461	29.8571939	2.933856945

(b)

Table 8.6(b) shows the percentage increase/decrease in WIP with three combinations (i.e. percentage increase/decrease from RF1 to SF3RF1, SF3 to RF1 and SF3 to SF3RF1). It is seen from the figure 8.6 that the maximum percentage decrease in the WIP is achieved when we switch the system from pure sequencing flexibility to the routing flexibility (i.e. SF3-RF1). The percentage decrease in WIP is maximum at SF3-RF1 with sequencing rule FCFS and minimum with FCLS. The performance of the system deteriorates with RF1-SF3RFI for all sequencing rules. There is marginal decrease in WIP with SF3-SF3RF1 system for all sequencing rules.

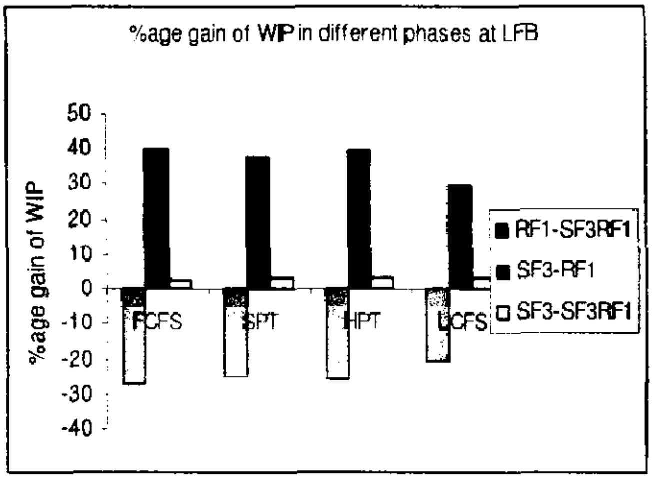


Figure 8.6: Percentage increase/decrease of WIP with LFB

Table 8.7(a) shows the combined effect of sequencing and routing flexibility on WIP at LBMUPT with sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively. It is seen from the table that WIP is maximum at SF3 with all sequencing rules than at RF1. Table 8.7(b) shows the percentage increase/decrease in WIP with three combinations (i.e. percentage increase from RF1 to SF3RF1, percentage decrease from SF3 to RF1 and percentage increase/decrease from SF3 to SF3RF1). It is seen from the figure 8.7 that the maximum percentage decrease in the value of WIP is achieved when we switch the system from pure sequencing flexibility to the routing flexibility (i.e. SF3-RF1). The percentage decrease in the value of WIP is maximum at SF3-RF1 with sequencing rule FCFS and minimum at SPT. The performance of the system deteriorates with RF1-SF3RFI for all sequencing rules. There is marginal increase/decrease in WIP with SF3-SF3RF1 system for all sequencing rules.

Table 8.7: WIP with different sequencing rule at LBMUPT

WIP LBMUPT			
	SF3	**RF1**	**SF3RF1**
FCFS	59.4925	40.6983333	57.574
SPT	54.796	41.1553333	56.24983333
HPT	59.6205	41.6845	57.702
LCFS	55.918	40.5655	53.83633333

(a)

Percentage increase/decrease of WIP at LBMUPT			
	RF1-SF3RF1	**SF3-RF1**	**SF3-SF3RF1**
FCFS	-29.3112632	46.1792047	3.3322333
SPT	-26.8347462	33.1443474	-2.58460025
HPT	-27.7590032	43.027984	3.324841427
LCFS	-24.6503291	37.8461994	3.866657586

(b)

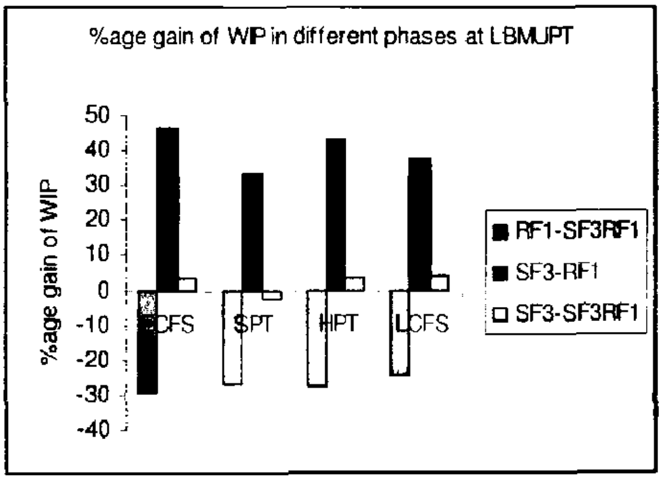


Figure 8.7: Percentage increase/decrease of WIP with LBMUPT

Table 8.8(a) shows the combine effect of sequencing and routing flexibility on WIP at LUMBPT with sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively. It is seen from the figure that WIP is maximum at SF3-RF1 with HPT and minimum at RF1 with LCFS. Table 8.8(b) shows the percentage improvement in the value of WIP with three combinations (i.e. percentage decrease from RF1 to SF3RF1, SF3 to RF1 and SF3 to SF3RF1). It is seen from the figure 8.8 that the maximum percentage decrease in the WIP is achieved when we switch the system from pure sequencing flexibility to routing flexibility (i.e. SF3-RF1). The percentage decrease in WIP is maximum at SF3-RF1 with sequencing rule HPT. The performance of the system deteriorates with RF1-SF3RFI for all sequencing rules.

Table 8.8: WIP with different sequencing rule at LUMBPT

WIP LUMBPT			
	SF3	**RF1**	**SF3RF1**
FCFS	53.19633333	41.631833	57.472
SPT	56.46183333	41.428833	53.0445
HPT	57.41466667	41.0305	57.702
LCFS	55.87716667	41.005167	53.83633333

(a)

Percentage increase/decrease of WIP at LUMBPT			
	RF1-SF3RF1	**SF3-RF1**	**SF3-SF3RF1**
FCFS	-27.5615372	27.778022	-7.43956478
SPT	-21.8979662	36.286322	6.442389566
HPT	-28.8924127	39.931677	-0.49796079
LCFS	-23.8336563	36.2686	3.790810419

(b)

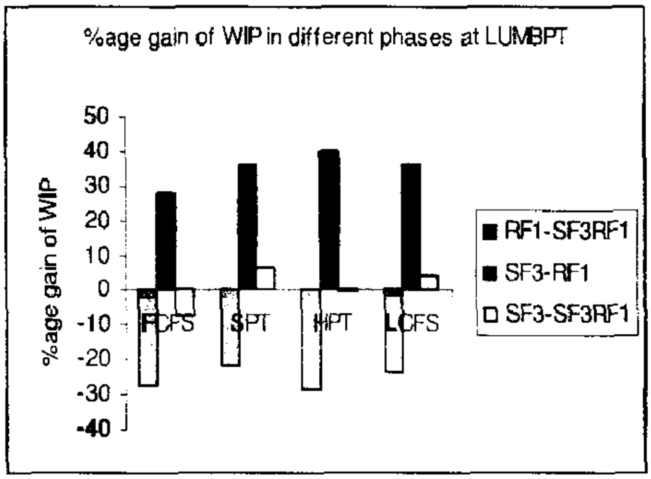


Figure 8.8: Percentage increase/decrease of WIP with LUMBPT

8.2.3. Combine Effect of SF and RF on RU at different load conditions

In this section we find the combined effect of sequencing and routing flexibility on resource utilization (RU) at different system load conditions. The figures 8.9 to 8.12

are drawn between RU and combined model at all four system load conditions. Tables 8.9 to 8.12 shows the RU value at SF3, RF1 and combined model under four system load conditions and four sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively.

Table 8.9(a) shows the combined effect of sequencing and routing flexibility on resource utilization (RU) at LUB with sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively. It is seen from the table that RU is minimum at all sequencing rules with sequencing flexibility and maximum at all sequencing rules with SF3-RF1. Table 8.9(b) shows the percentage improvement in RU with three combinations (i.e. percentage gain from RF1 to SF3RF1, SF3 to RF1 and SF3 to SF3RF1). It is seen from the figure 8.9 that the maximum percentage gain in the RU is achieved when we switch the system from pure sequencing flexibility to combined flexibility (i.e. SF3-SF3RF1). The percentage gain in RU is maximum for SF3RF1 with sequencing rule HPT and minimum with sequencing rule SPT.

Table 8.9: RU with different sequencing rule at LUB

RU LUB			
	SF3	**RF1**	**SF3RF1**
FCFS	0.817687	0.94715	0.992825
SPT	0.82002	0.962718	0.988668
HPT	0.791748	0.905477	0.982532
LCFS	0.806217	0.941475	0.973628

(a)

Parentage increase RU at LUB			
	RF1-SF3RF1	**SF3-RF1**	**SF3-SF3RF1**
FCFS	4.600509	13.66873	17.6404
SPT	2.624743	14.82244	17.05813
HPT	7.842495	12.56005	19.41753
LCFS	3.302424	14.36664	17.19462

(b)

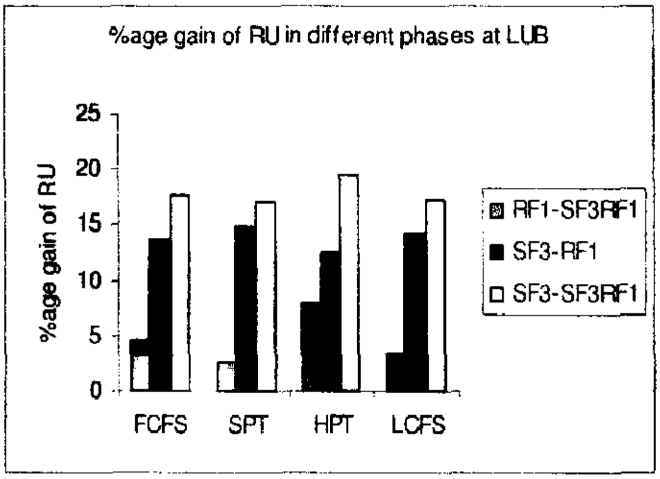


Figure 8.9: Percentage increase of RU with LUB

Table 8.10(a) shows the combined effect of sequencing and routing flexibility on RU at LFB with sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively. It is seen from the table that RU is minimum at all sequencing rules with sequencing flexibility i.e. SF3 and maximum at all sequencing rules with SF3RF1. Table 8.10(b) shows the percentage improvement in RU with three combinations (i.e. percentage increase from RF1 to SF3RF1, SF3 to RF1 and SF3 to SF3RF1). It is seen from the figure 8.10 that the maximum percentage gain in the RU is achieved when we switch the system from pure sequencing flexibility to combined flexibility (i.e. SF3-SF3RF1). The percentage gain in RU is maximum at SF3 to SF3RF1 with sequencing rule HPT and minimum at RF1-SF3RF1 with sequencing rule LCFS.

Table 8.10: RU with 4 different sequencing rule at LFB

RU LFB			
	SF3	**RF1**	**SF3RF1**
FCFS	0.823002	0.960045	0.993085
SPT	0.821588	0.964258	0.986717
HPT	0.809593	0.933293	0.986452
LCFS	0.814068	0.947528	0.97564

(a)

Percentage increase of RU at LFB			
	RF1-SF3RF1	SF3-RF1	SF3-SF3RF1
FCFS	3.327006	14.27468	17.1267649
SPT	2.276067	14.79583	16.7351317
HPT	5.388843	13.25414	17.9287378
LCFS	2.881357	14.08507	16.5605825

(b)

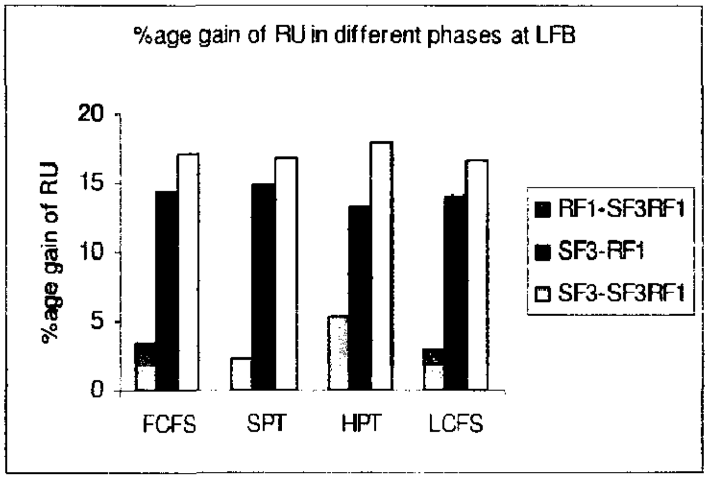


Figure 8.10: Percentage increase of RU with LFB

Table 8.11(a) shows the combined effect of sequencing and routing flexibility on RU at LBMUPT with sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively. It is seen from the table that RU is minimum at all sequencing rules with sequencing flexibility and maximum at all sequencing rules with SF3RF1.

Table 8.11: RU with 4 different sequencing rule at LBMUPT

RU LBMUPT			
	SF3	RF1	SF3RF1
FCFS	0.81756	0.958762	0.99308
SPT	0.811802	0.9618	0.988098
HPT	0.790592	0.93265	0.984257
LCFS	0.808827	0.95387	0.977947

(a)

Percentage gain of RU at LBMUPT			
	RF1-SF3RF1	SF3-RF1	SF3-SF3RF1
FCFS	3.455747	14.7275	17.6743062
SPT	2.66151	15.59558	17.8420164
HPT	5.243212	15.23169	19.6762701
LCFS	2.461961	15.20578	17.2933766

(b)

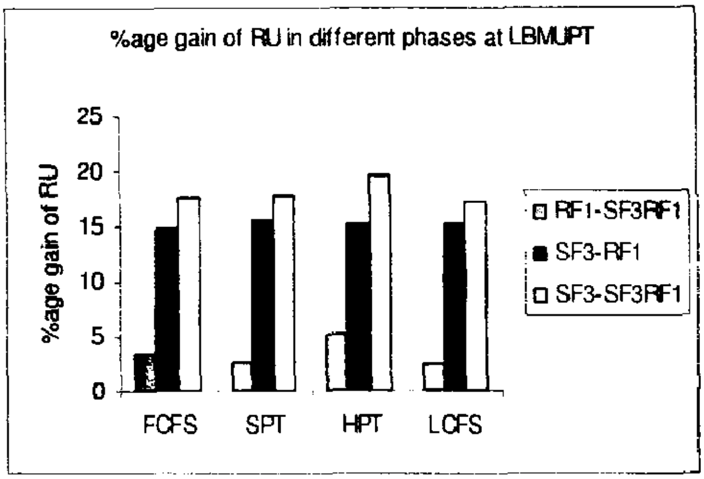


Figure 8.11: Percentage increase of RU with LBMUPT

Table 8.11(b) shows the percentage improvement in RU with three combinations (i.e. %age gain from RF1 to SF3RF1, SF3 to RF1 and SF3 to SF3RF1). It is seen from the figure 8.11 that the maximum percentage gain in the RU is achieved when we switch the system from pure sequencing flexibility to combined flexibility (i.e. SF3-SF3RF1). The percentage increase in RU is maximum at SF3 to SF3RF1 with sequencing rule HPT and minimum at RF1-SF3RF1 with sequencing rule LCFS.

Table 8.12(a) shows the combined effect of sequencing and routing flexibility on RU at LUMBPT with sequencing rules i.e. FCFS, SPT, HPT and LCFS respectively.

Table 8.12: RU with 4 different sequencing rule at LUMBPT

RU LUMBPT			
	SF3	**RF1**	**LUMBPT**
FCFS	0.819808	0.958692	0.993768
SPT	0.821713	0.962427	0.98526
HPT	0.812617	0.938675	0.984257
LCFS	0.816607	0.951953	0.977947

(a)

Percentage increase of RU at LUMBPT			
	RF1-SF3RF1	**SF3-RF1**	**SF3-SF3RF1**
FCFS	3.529662	14.48676	17.50508589
SPT	2.317493	14.62068	16.59934095
HPT	4.631075	13.42939	17.43854076
LCFS	2.65795	14.21778	16.49783219

(b)

It is seen from the figure that RU is minimum at all sequencing rules with sequencing flexibility and maximum at all sequencing rules with SF3RF1. Table 8.12(b) shows the percentage improvement in RU with three combinations (i.e. percentage increase from RF1 to SF3RF1, SF3 to RF1 and SF3 to SF3RF1). It is seen from the table 8.12 that the maximum percentage gain in the RU is achieved when we switch the system from pure sequencing flexibility to combined flexibility (i.e. SF3-SF3RF1). The percentage gain in RU is maximum at SF3 to SF3RF1 with sequencing rule HPT and minimum at LCFS.

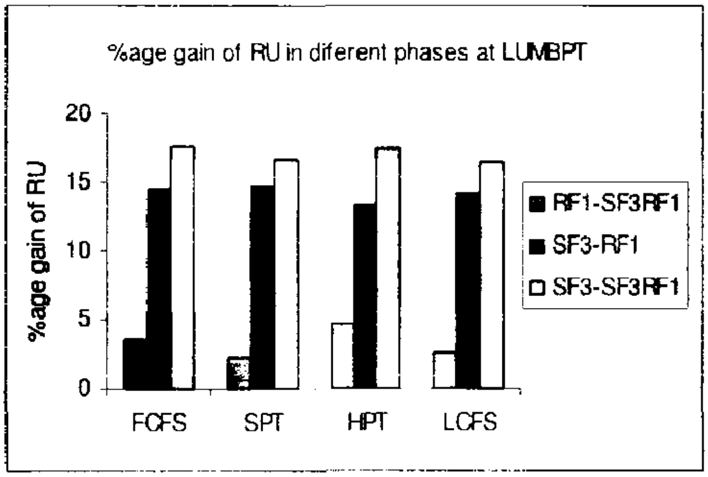


Figure 8.12: Percentage increase of RU with LUMBPT

8.3 Conclusion

In this chapter, the simulation experiments were carried out with four load conditions (i.e. LUB, LFB, LBMUPT, and LUMBPT) and four sequencing rules (i.e. FCFS, SPT, HPT, and LCFS) at combined model of sequencing and routing flexibility. The performance of the system was measured by three performance measures like make-span (MST), work-in-process (WIP) and resource utilization (RU). It is found that the system performs differently at different performance measures, system load conditioned and sequencing rules for different combination of manufacturing flexibility. If one considers MST as performance measure then MST is minimum for FCFS sequencing rule for all system load conditions when the system is operated combined sequencing and routing flexibility. However when WIP is considered as performance measure then WIP is minimum for LCLS when the system is operated with LUB, LBMUPT and LUMBPT system load conditions. SPT sequencing rule performs better when the system is run with LFB system load condition. We achieve minimum WIP when the system is operated with routing flexibility level 1. This further shows that the system performance deteriorates when the system is operated with combined sequencing and routing flexibility. Now with RU as performance measure RU maximum again for FCFS sequencing rule for all system load conditions when the system is operated combined sequencing and routing flexibility.

Chapter 9

Study of key Factors, its Contribution and Interactions in SFMS: Taguchi Method

9.1 Introduction

In chapter 6, 7 and 8 our aim was to study the impact of individual factors related to design, planning and control decisions on the SFMS performance. We performed a simulation study based on one factor change at a time. For instance in chapter 5, we introduced sequencing flexibility and studied its impact on planning and control decisions. In chapter 6, we studied the impact of routing flexibility under different planning and control decisions. In chapter 7, we studied the impact of AGVs under different planning and control decisions. In chapter 8 the combined effect of sequencing and routing flexibility is studied under different planning and control decisions. Simulation study was performed to take into consideration the change in one factor at a time. In general the planning of simulation study depends on the purpose and motivation. SFMS being a new theme, we were motivated to develop it in phased manner. We studied its performance by taking into consideration individual factors to develop a better insight about the system. After having shown the importance of explicitly modeling design, planning and control decisions in SFMS, we identified one difficulty for the practitioners. It appeared that SFMS designers and controller may find the study one factor at a time, too time consuming to be of a practical value. Practitioners are often more concerned about understanding the priority factors to focus on while taking design, planning and control decisions for phased development of SFMS. They aim of this work is to obtain quick insight of the relative contribution of the priority decisions factors on the performance of the system. The practitioner may face a situation where they have to operate the system at a certain levels of decision factors and decide to operate the system at some other level with respect to some other factors. The key challenge is to know the preferable new levels i.e., which levels to simultaneously change and which not to change. Keeping in view these requirements we were motivated to explore the use of Taguchi methods to guide our simulation study. The Taguchi methods provide a means to study a number of factors at different levels simultaneously. As we are aware that simulation provided in a "what if" analysis for the changes made in the various factors one at a time. Simulation approach helped us our primary modeling purpose of getting a detailed insight on the role of individual factors of interest. A simulation study carried out in earlier chapters was not aimed at identifying the amount of contribution that the interaction between assumed factors have on the performance of SFMS.

9.2 Application of Taguchi's design of Experiments

The Taguchi design was used to determine optimal design, planning and control decisions factors and to know the relationships between independent variables and makespan (MST), work-in-process (WIP) and resource utilization (RU) performance measures of the SFMS. Taguchi methods suggest the use of experimental design procedure which standardizes an array of experiments with respect to the number of factors and their levels to be studied. The columns of an orthogonal array are pair wise orthogonal, i.e., for every pair of columns, all combinations of factor levels occurs an equal number of times. The columns of the orthogonal array represent factors to be studied and the rows represent the number of experiments. After conducting a matrix experiment, the data from all the experiments in the set taken together is analyzed to determine the effects of the various factors. After performing a series of experiments, the simulation results are transformed into a signal-to-noise (S/N) ratio. Taguchi recommends the use of S/N ratio to measure the quality characteristics of the response parameters. Usually, there are three categories of S/N ratio to measure the quality characteristic. These are the-smaller-the-better, the-higher-the-better, and the nominal-the-better. Regardless of the category of the quality characteristic, a greater ratio corresponds to better quality characteristics. Therefore, the optimal level of the process parameters is the level with the greatest S/N ratio. The experiments have been carried out by using the standardized Taguchi-based experimental design, a L_{16} (4^4) orthogonal arrays, with four levels (coded by: 1, 2, 3 and 4) of four decisions parameters (see Table 9.1).

Our motivation is to demonstrate the use of Taguchi methods in SFMS domain where one may be interested to identify not only the factor level effects but also the interaction effects. The implementation of design, planning and control decisions within the evolving SFMS is characterized by continuous change. Within such turbulent environment it is important the system operates under appropriate levels of design, planning and control decisions as well as understanding of how it may be affected by other factors. In this chapter we are motivated to use Taguchi method to study the contribution of individual factors and their interactions. Our motivation here is in outlining a methodology which would help system designer's to find out the performance of the system.

Table 9.1: Taguchi's standard L_{16} (4^4) orthogonal array

	Factors			
Factors levels	1	1	1	1
	1	2	2	2
	1	3	3	3
	1	4	4	4
	2	1	2	3
	2	2	1	4
	2	3	4	1
	2	4	3	2
	3	1	3	4
	3	2	4	3
	3	3	1	2
	3	4	2	1
	4	1	4	2
	4	2	3	1
	4	3	2	4
	4	4	1	3

According to Phadke (1989), the natural scale of the response is not suitable for analyzing the performance because it gives a negative prediction for the response, which is absurd. By using the decibel scale, it will be able to avoid the negative prediction. Thus, in order to minimize the sensitivity to noise factors, we maximize S/N (α) ratio, which is given as:

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{9.1}$$

In this equations, y_i is the experimental value, and n is number of times doing the same experiment. In our work the responses are MST, WIP and RU. For MST and WIP we considered smaller-the-best for the analysis. In case of RU, the larger-the-best was taken for the analysis.

9.3 Experimental results of SFMS with sequencing flexibility

With reference to table 9.1, table 9.2 is constructed to design simulation experiment using Taguchi method. In the simulation experiment six parts of 100 units are produced. In all the MST, WIP and RU are collected for the total of 600 parts. We have considered four decisions factors (sequencing flexibility, system capacity, system load condition and sequencing rules) with four levels. If the simulation experiments are performed with all the four factors at all the four levels, then the number of experiments would be 4^4, i.e., 256. With Taguchi's method the number of simulation experiments drop to only 16. The results obtained are shown in table 9.3.

Table 9.2: Physical and coded values of decisions factors for Taguchi's design of experiment (SF)

Symbols	Factors	Levels			
	Coding- Orthogonal array	1	2	3	4
SF	Sequencing flexibility	SF0	SF1	SF2	SF3
SC	System capacity	30	60	90	120
SL	System load conditions	LFB	LUB	LUMBPT	LBMUPT
SR	Sequencing flexibility	FCFS	SPT	HPT	LCFS

Table 9.3: Orthogonal array $L_{16}(4)$ with experimental results and calculated S/N ratios

Exp. No.	SF	SC	SL	SR	MST/ min.	S/N ratio/ (dB)	WIP (%)	S/N ratio/ (dB)	RU (%)	RU ratio/ (dB)
1	1	1	1	1	31397	-89.94	45.60	-33.18	0.44	7.13
2	1	2	2	2	19761	-85.92	42.59	-32.59	0.70	3.12
3	1	3	3	3	17268	-84.75	42.72	-32.61	0.79	2.04
4	1	4	4	4	17596	-84.91	42.88	-32.65	0.77	2.26
5	2	1	2	3	27924	-88.92	44.04	-32.88	0.47	6.62
6	2	2	1	4	18657	-85.42	45.20	-33.10	0.75	2.53
7	2	3	4	1	17270	-84.75	46.23	-33.30	0.78	2.14
8	2	4	3	2	16971	-84.59	48.92	-33.79	0.78	2.06
9	3	1	3	4	23600	-87.46	48.62	-33.74	0.46	6.83
10	3	2	4	3	15428	-83.77	51.38	-34.22	0.75	2.54
11	3	3	1	2	14419	-83.18	53.90	-34.63	0.79	2.05
12	3	4	2	1	14814	-83.41	54.10	-34.66	0.78	2.20
13	4	1	4	2	17662	-84.94	45.98	-33.25	0.77	2.26
14	4	2	3	1	17618	-84.92	44.88	-33.04	0.77	2.25
15	4	3	2	4	17988	-85.10	45.14	-33.09	0.72	2.82
16	4	4	1	3	16801	-84.51	58.30	-35.3143	0.82	1.76

According to the Taguchi experimental framework, the analysis of means (ANOM) can be used to achieve the best optimal factor combination.

9.3.1 Optimal factor combinations (SF)

In order to find the optimal factor combinations for the given SFMS model, the ANOM can be used and the formula is defined as below (Phadke 1989):

m_{jk} = main factor effect for the k_{th} level of factor j, i.e.:

$$\sum_{i=1}^{l} = \frac{\alpha_{jki}}{l} \qquad \textbf{9.2}$$

Where: j = the factor (i.e., sequencing flexibility, system capacity, system load, sequencing rules); k = factor level; α_{jki} = the S/N ratio of the factor j with level k; l = the time that factor j with level k appears in the simulation model.

With reference to the ANOM, the m_{jk} values for SFMS with the three measuring parameters MST, WIP and RU are presented in Tables 9.4. The S/N ratio is used for the representation so that the optimal levels for each factor can be represented by the maximum point in the graph as shown in the figure 9.1, 9.2 and 9.3.

Table 9.4: Factor mean effects of matrix experiment (SF)

Factor level Main effect	Applicable formula	MST S/N (α) ratio (dB)	WIP S/N (α) ratio (dB)	RU S/N (α) ratio (dB)
m_{SF0}	(α1+ α2+ α3+ α4)/4	-86.38	-32.76	3.64
m_{SF1}	(α5+ α6+ α7+ α8)/4	-85.92	-33.27	3.34
m_{SF2}	(α9+ α10+ α11+ α12)/4	-84.45	-34.31	3.41
m_{SF3}	(α13+ α14+ α15+ α16)/4	-84.87	-33.67	2.27
m_{SC1}	(α1+ α5+ α9+ α13)/4	-87.81	-33.26	5.70
m_{SC2}	(α2+ α6+ α10+ α14)/4	-85.00	-33.24	2.61
m_{SC3}	(α3+ α7+ α11+ α15)/4	-84.44	-33.41	2.26
m_{SC4}	(α4+ α8+ α12+ α16)/4	-84.36	-34.10	2.07
m_{SL1}	(α1+ α6+ α11+ α16)/4	-85.76	-34.05	3.37
m_{SL2}	(α2+ α5+ α12+ α15)/4	-85.84	-33.29	3.69
m_{SL3}	(α3+ α8+ α9+ α14)/4	-85.43	-33.29	3.29
m_{SL4}	(α4+ α7+ α10+ α13)/4	-84.59	-33.35	2.30
m_{SR1}	(α1+ α7+ α12+ α14)/4	-85.75	-33.54	3.43
m_{SR2}	(α2+ α8+ α11+ α13)/4	-84.66	-33.56	2.37
m_{SR3}	(α3+ α5+ α10+ α16)/4	-85.48	-33.75	3.23
m_{SR4}	(α4+ α6+ α9+ α15)/4	-85.72	-33.14	3.61

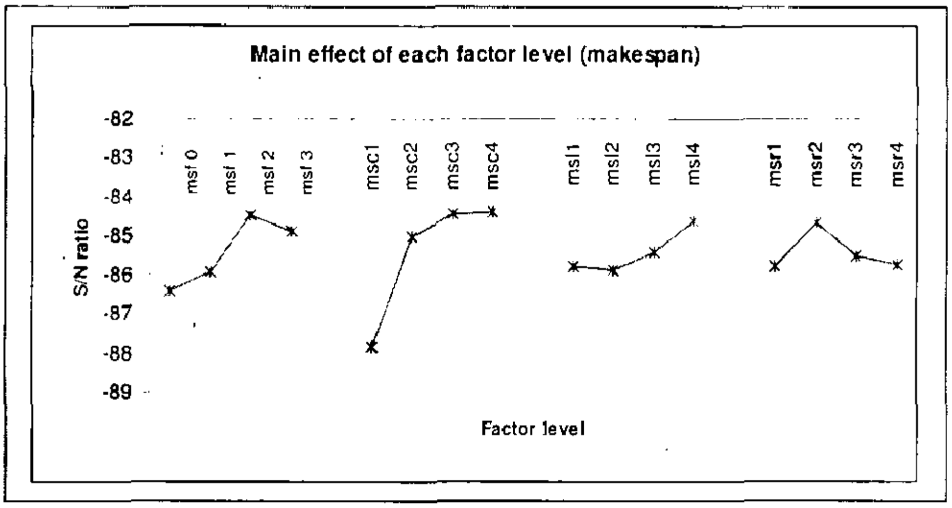


Figure 9.1: Main effects of each factor level (MST)

Figure 9.1, which show the main effects of each factor level. It can be found that the best factor level combination under MST is SF2, SC3, SL4 and SR2. This can be easily interpreted as the sequencing flexibility level 3, the system capacity 90, load balanced on machine and unbalanced processing time (LBMUPT), and the sequencing rule as SPT.

Figure 9.2 shows the main effects of each factor level, it can be found that the best factor level combination under the measurement of WIP is SF0, SC2, SL2 and SR4. This can be easily interpreted as the sequencing flexibility level 1, the system capacity 60, load fully unbalanced (LUB), and the sequencing rule as LCFS.

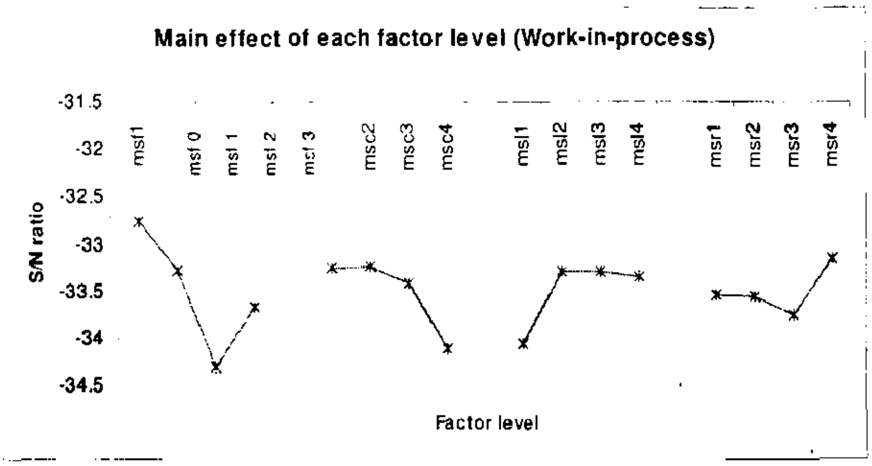


Figure 9.2: Main effects of each factor level (WIP)

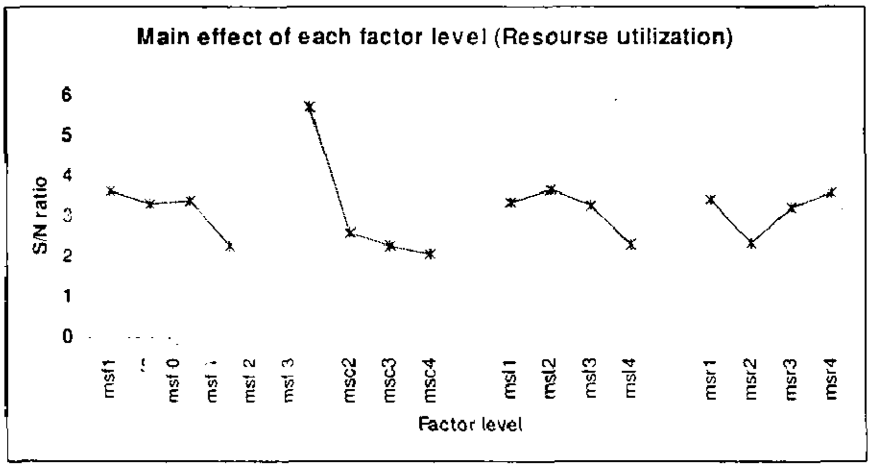


Figure 9.3: Main effects of each factor level (RU)

Figure 9.3 shows the main effects of each factor level. It is seen that the best factor level combination under the measurement of RU is SF0, SC1, SL2 and SR4. This means that sequencing flexibility level is 1, the system capacity is 30, system load condition is, load fully unbalanced (LUB), and the sequencing rule is LCFS. In addition to the above analysis, the relative significance of different factors on the system is also very important. To know the relative significance of different factors ANOVA was performed. The details are discussed in the following sections.

9.3.2 Analysis of variance (SF)

The ANOVA table is calculated using the Minitab statistical software at 95% confidence level. In fact, the relative importance of the factor is shown by the error variance. The larger the value is, the more important the factor. The simulation results of the MST, WIP and RU of the system (see Table 9.3) are chosen for constructing the ANOVA table 9.5. As suggested by Phadke (1989), the F-value is an indicator of the importance of that factor. From table 9.5 it is observed that the F-value of the system capacity is the highest at MST and RU measure while the sequencing flexibility is dominated at WIP measure, whereas the sequencing rules are the least significant at all performance measures.

Table 9.5: ANOVA of the simulation results at different outputs (SF)

ANOVA for Means (MST)						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
SF	3	54605388	54605388	18201796	2.29	0.257
SC	3	200724829	200724829	66908276	8.42	0.057
SL	3	28146898	28146898	9382299	1.18	0.447
SR	3	20676354	20676354	6892118	0.87	0.545
Residual Error	3	23834770	23834770	7944923		
Total	15	327988239				
ANOVA Means (WIP)						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
SF	3	159.20	159.20	53.066	11.26	0.039
SC	3	68.67	68.67	22.89	4.86	0.113
SL	3	55.54	55.54	18.512	3.93	0.145
SR	3	27.59	27.59	9.196	1.95	0.298
Residual Error	3	14.14	14.14	4.714		
Total	15	325.14				
ANOVA for Means (RU)						
SF	3	0.02151	0.02151	0.007169	0.96	0.512
SC	3	0.16797	0.16797	0.055991	7.52	0.066
SL	3	0.02168	0.02168	0.007226	0.97	0.510
SR	3	0.01716	0.01716	0.005721	0.77	0.583
Residual Error	3	0.02234	0.02234	0.007446		
Total	15	0.25066				

9.3.3 Normal probability plot (SF)

The main assumptions for using ANOVA is that the sample data used should be normally distributed and have equal variances. The normality of the data can be checked with a normal probability plot of residuals. If the plot is a straight line then it confirms that the distribution of residuals is normal. The variance is constant if the residuals versus fitted value plot do not follow any pattern. Figures 9.4, 9.6 and 9.8 show the normality plot of the residuals for MST, WIP and RU utilization respectively. It is observed from the plot that the residuals follow the normal distribution.

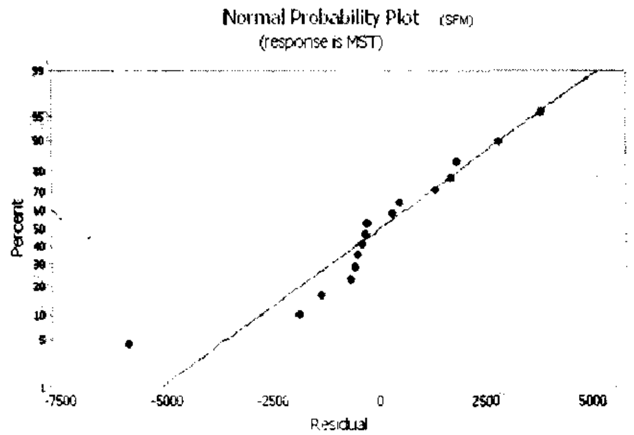


Figure 9.4: Normality plot of residuals for MST (SF)

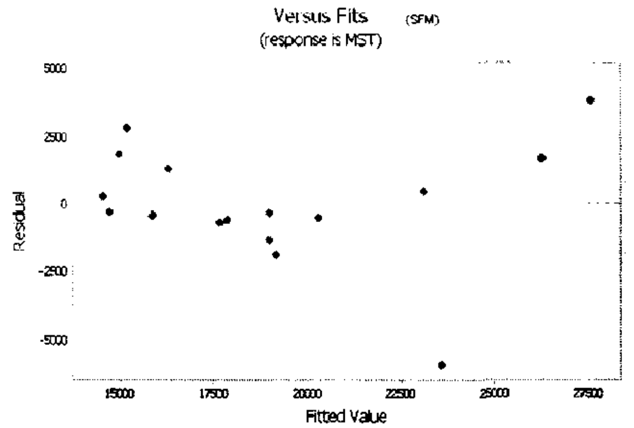


Figure 9.5: Residuals versus fitted values plot for MST (SF)

Figure 9.5, 9.7 and 9.9 are drawn between the residuals and fitted value for the MST, WIP and RU respectively that does not shows any pattern. Thus the assumptions of normality and constant variance are satisfied.

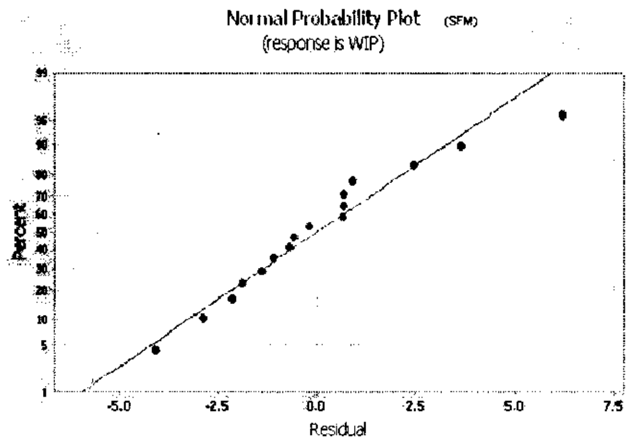


Figure 9.6: Normality plot of residuals for WIP (SF)

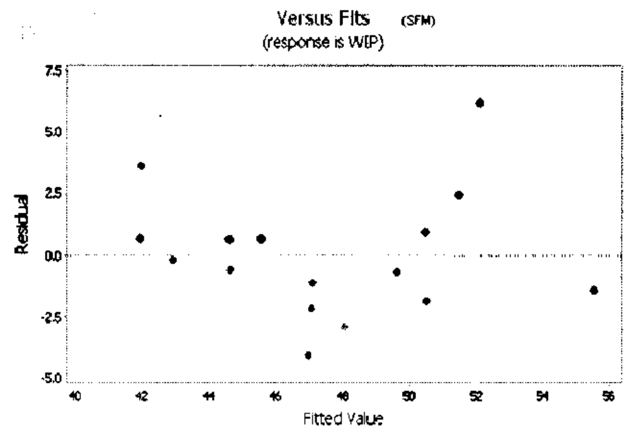


Figure 9.7: Residuals versus fitted values plot for WIP (SF)

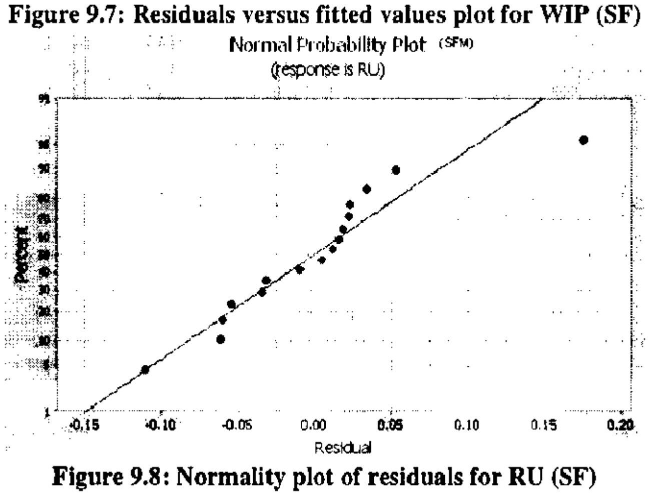


Figure 9.8: Normality plot of residuals for RU (SF)

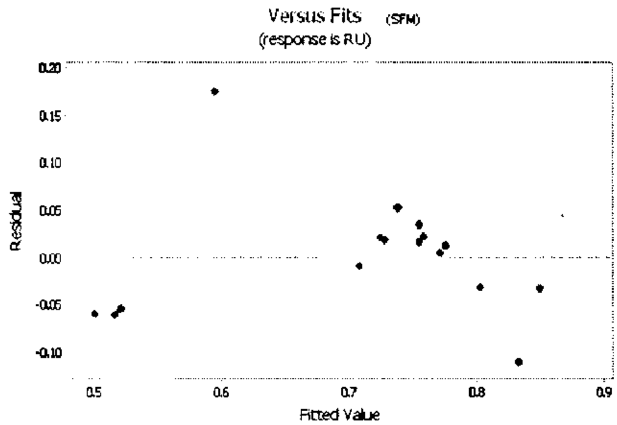


Figure 9.9: Residuals versus fitted values plot for RU (SF)

9.3.4 Confirmation experiment (SF)

On the basis of S/N ratio and ANOVA analysis, the optimal levels of all the decisions factors were identified. As mentioned earlier the optimum decisions factors for MST under sequencing flexibility are SF2, SC3, SL4 and SR2. The objective of confirmation experiment is to verify the optimum conditions suggested by the matrix experiment. The predicted value of S/N ratio at optimum level (η_o) is calculated by the relation (9.3).

$$\eta_o = \eta_m + \sum_{i=1}^{j} (\eta_i - \eta_m) \qquad 9.3$$

Where j is the number of factors and η_m is the mean value of S/N ratios in all the experimental runs η_i are the S/N ratios corresponding to optimum factor levels (Ross 1996, Dubey et al 2007).

9.3.4.1: S/N ratio calculation at optimal level

For MST under sequencing flexibility

$$\eta_o = \eta_m + (\eta_{sf2} - \eta_m) + (\eta_{sc3} - \eta_m) + (\eta_{sl4} - \eta_m) + (\eta_{sr2} - \eta_m) \qquad 9.4$$

Where;

η_o is optimum S/N ratio

η_m is the overall mean of S/N ratio

η_{sf2} is the average value of S/N ratio at third level of sequencing flexibility

η_{sc3} is the average value of S/N ratio at third level of system capacity (90)

η_{sl4} is the average value of S/N ratio at fourth level of system load condition (LBMUPT)

η_{sr2} is the average value of S/N ratio at second level of sequencing rule (SPT)

From the table 9.4, we have

$\eta_m = -85.4044$ $\eta_{sf2} = -84.4544$ $\eta_{sc3} = -84.4426$ $\eta_{sl4} = -85.5906$

$\eta_{sc3} = -84.6577$

$\eta_o = -85.4044 + (-84.4544+85.4044) + (-84.4426+85.4044) + (-85.5906+85.4044) + (-84.6577+85.4044)$

$\eta_o = -82.932$

If the optimum S/N ratio is known, the value of MST can be determined by the equation 9.1. The procedure is to back-transform S/N ratio to find expected performance value (Roy 2001, Savaskan 2003). When the optimum S/N ratio obtained by equation 9.4 is placed in equation 9.1, the expected performance for the MST comes out to be

$$S/N = -10\log(\frac{1}{n}\sum_{i=1}^{n} MST^2)$$

$$-82.932 = -10 \log (MST)^2$$

$$-82.932 = -20 \log (MST)$$

$$MST = 14015.2$$

For WIP and RU the same procedure is followed for calculating the optimum S/N ratio and the expected performance value. The results are tabulated in the table 9.6 given below.

Table 9.6: Results of confirmation experiment (SF)

	Optimal parameters for sequencing flexibility	
	Prediction	Experimental
Level	**SF2 SC3 SL4 SR2**	**SF2 SC3 SL4 SR2**
MST	14015.2	17520.9
S/N ratio	-82.93	-84.87
Level	**SF0 SC2 SL2 SR4**	**SF0 SC2 SL2 SR4**
WIP	39.48	43.90
S/N ratio	-31.92	-32.85
Level	**SF0 SC1 SL2 SR4**	**SF0 SC1 SL2 SR4**
RU	0.4388	0.4251
S/N ratio	7.1542	7.430

From the above analysis it is seen that the best factor level combinations under MST is **SF2,** SC3, **SL4** and **SR2. This** can be interpreted as the sequencing flexibility level 3, system capacity 90, load balanced on machine and unbalanced processing time (LBMUPT), and sequencing rule as SPT where as in case of WIP, **SF0** SC2 **SL2 SR4** is **the best** combinations. This can be interpreted as the sequencing flexibility level 1, the system capacity 60, load fully unbalanced (LUB), and sequencing rule as LCFS. Similarly for RU the best combinations are SF0, **SC1, SL2 and SR4. This** can be interpreted as the sequencing flexibility level 1, system capacity 30, load fully unbalanced (LUB) and sequencing rule as LCFS.

9.4 Experimental results of SFMS with routing flexibility

With the help of table 9.1, table 9.7 was developed for Taguchi's design of experiment when the system is operating under routing flexibility. The results obtained are shown in table 9.8.

Table 9.7: Physical and coded values of decisions factors for Taguchi's design of experiment (RF)

Symbols	Factors	Levels			
	Coding- Orthogonal array	1	2	3	4
RF	Routing flexibility	RF0	RF1	RF2	RF3
SC	System capacity	30	60	90	120
SL	System load conditions	LFB	LUB	LUMBPT	LBMUPT
SR	Sequencing rules	FCFS	SPT	HPT	LCFS

Table 9.8: Orthogonal array $L_{16}(4)$ with experimental results and calculated S/N ratios (RF)

Exp. No.	RF	SC	SL	SR	MST/ min.	S/N ratio/ (dB)	WIP (%)	S/N ratio/ (dB)	RU (%)	RU ratio/ (dB)
1	1	1	1	1	31397	-89.93	45.59	-33.17	0.43	7.25
2	1	2	2	2	19761	-85.91	42.58	-32.58	0.69	3.16
3	1	3	3	3	18347	-85.27	43.26	-32.72	0.74	2.59
4	1	4	4	4	17596	-84.90	42.88	-32.64	0.77	2.22
5	2	1	2	3	31897	-90.07	44.52	-32.97	0.42	7.35
6	2	2	1	4	18606	-85.39	42.10	-32.48	0.73	2.70
7	2	3	4	1	15161	-83.61	40.78	-32.20	0.89	0.95
8	2	4	3	2	14142	-83.01	41.42	-32.34	0.96	0.33
9	3	1	3	4	32797	-90.31	43.46	-32.76	0.41	7.63
10	3	2	4	3	18910	-85.53	40.82	-32.21	0.71	2.87
11	3	3	1	2	14836	-83.42	40.44	-32.13	0.91	0.77
12	3	4	2	1	13903	-82.86	43.77	-32.82	0.98	0.14
13	4	1	4	2	32534	-90.24	42.96	-32.66	0.41	7.55
14	4	2	3	1	14795	-83.40	41.06	-32.26	0.91	0.74
15	4	3	2	4	14266	-83.08	42.41	-32.54	0.95	0.36
16	4	4	1	3	14258	-83.08	42.30	-32.52	0.95	0.41

According to the Taguchi experimental framework, the analysis of means (ANOM) can be used to achieve the best optimal factor combination.

9.4.1 Optimal factor combinations (RF)

With reference to the ANOM, the m_{jk} values for SFMS with the three measuring parameters MST, WIP and RU are presented in Tables 9.9. The S/N ratio was used for the representation rather than the observed readings so that the optimal levels for each factor can be represented by the maximum point in the graph shows in the figure 9.10, 9.11 and 9.12.

Table 9.9: Factor mean effects of matrix experiment (RF)

Factor level Main effect	Applicable formula	MST S/N (α) ratio (dB)	WIP S/N (α) ratio (dB)	RU S/N (α) ratio (dB)
m_{SF0}	(α1+ α2+ α3+ α4)/4	-86.51	-32.78	3.80
m_{SF1}	(α5+ α6+ α7+ α8)/4	-85.52	-32.50	2.83
m_{SF2}	(α9+ α10+ α11+ α12)/4	-85.53	-32.48	2.85
m_{SF3}	(α13+ α14+ α15+ α16)/4	-84.95	32.50	2.27
m_{SC1}	(α1+ α5+ α9+ α13)/4	-90.14	-32.89	7.44
m_{SC2}	(α2+ α6+ α10+ α14)/4	-85.06	-32.38	2.37
m_{SC3}	(α3+ α7+ α11+ α15)/4	-83.84	-32.40	1.17
m_{SC4}	(α4+ α8+ α12+ α16)/4	-83.46	-32.58	0.77
m_{SL1}	(α1+ α6+ α11+ α16)/4	-85.45	-32.58	2.78
m_{SL2}	(α2+ α5+ α12+ α15)/4	-85.48	-32.73	2.75
m_{SL3}	(α3+ α8+ α9+ α14)/4	-85.50	-32.52	2.82
m_{SL4}	(α4+ α7+ α10+ α13)/4	-86.07	-32.43	3.40
m_{SR1}	(α1+ α7+ α12+ α14)/4	-84.95	-32.62	2.27
m_{SR2}	(α2+ α8+ α11+ α13)/4	-85.65	-32.43	2.95
m_{SR3}	(α3+ α5+ α10+ α16)/4	-85.99	-32.61	3.30
m_{SR4}	(α4+ α6+ α9+ α15)/4	-85.92	-32.61	3.23

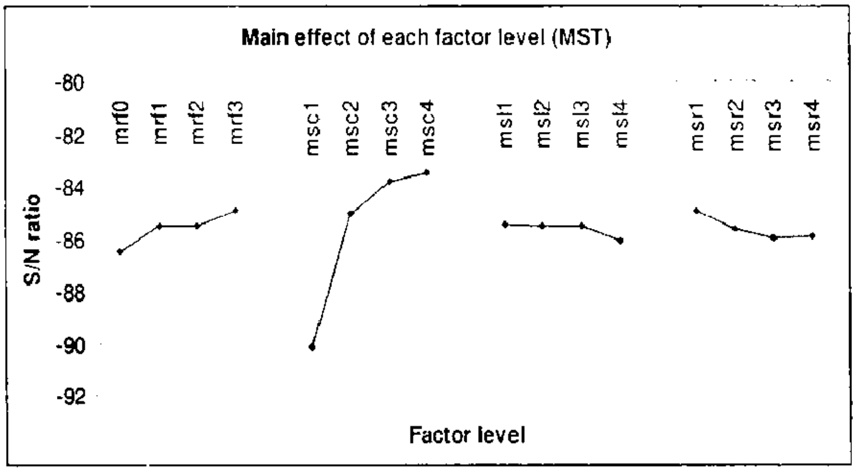


Figure 9.10: Main effects of each factor level (MST)

Figure 9.10, shows the main effects of each factor level. It can be found that the best factor level combinations under MST are RF3, SC4, SL1 and SR1. This can be easily interpreted as the routing flexibility level 4, the system capacity 120, load fully balanced (LFB) and sequencing rule as FCFS.

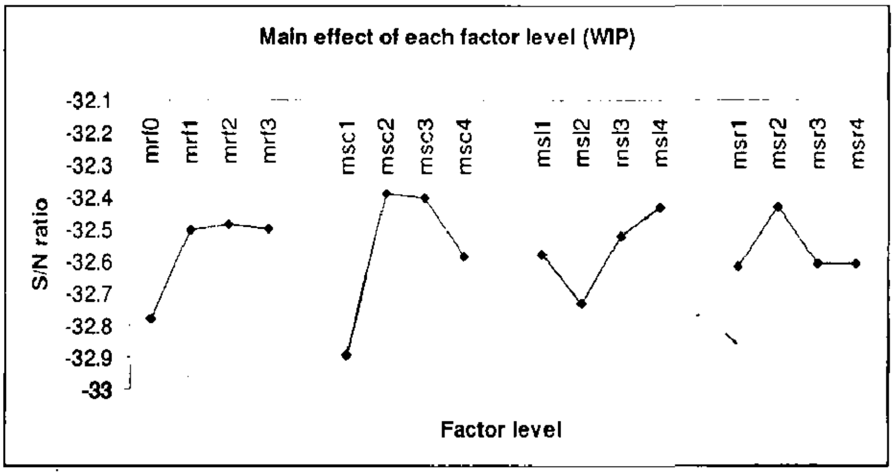


Figure 9.11: Main effects of each factor level (WIP)

Figure 9.11 shows the main effects of each factor level. It can be found that the best factor level combinations under WIP are RF2, SC2, SL4 and SR2. This can be easily interpreted as the routing flexibility level 3, the system capacity 60, load balanced on machine and unbalanced processing time (LBMUPT) and sequencing rule as SPT. Figure 9.12 shows the main effects of each factor level. It can be found that the best factor level combinations under RU utilization are RF0, SC1, SL4 and SR3.

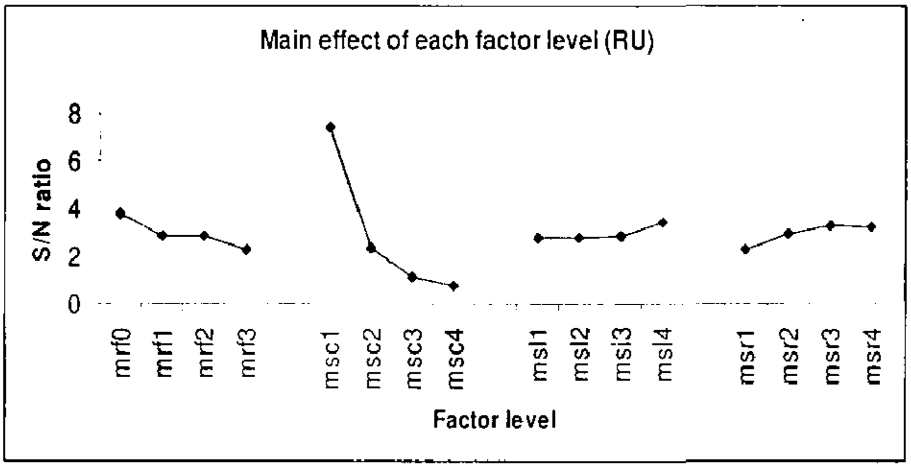


Figure 9.12: Main effects of each factor level (RU)

This can be easily interpreted as the routing flexibility level 1, the system capacity 30, load balanced on machine and unbalanced processing time (LUMBPT), and the sequencing rule is HPT.

In addition to the above analysis, the relative significance of different factors is also very important. In this connection, the impact of factors, acting on the system were determined by ANOVA. The simulation results of the MST, WIP and RU of the system (see Tables 9.8) were chosen for constructing the ANOVA table (Table 9.10). According to Table 9.10, the F-value of the system capacity is the highest at MST, RU as well at WIP. Where as the system load condition is the least significant at MST and RU while the sequencing rules is at WIP in the given models.

Table 9.10: ANOVA showing the simulation results at different outputs (RF)

ANOVA for Means (MST)						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
RF	3	16320178	16320178	5440059	4.28	0.132
SC	3	782739183	782739183	260913061	205.32	0.001
SL	3	3983854	3983854	1327951	1.05	0.486
SR	3	10964563	10964563	3654854	2.88	0.204
Residual Error	3	3812234	3812234	1270745		
Total	15	817820013				
ANOVA for Means (WIP)						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
RF	3	5.9762	5.9762	1.9921	3.74	0.154
SC	3	16.0854	16.0854	5.3618	10.06	0.045
SL	3	4.5263	4.5263	1.5088	2.83	0.208
SR	3	2.4233	2.4233	0.8078	1.52	0.370
Residual Error	3	1.5983	***1.5983***	0.5328		
Total	15	30.6095				
ANOVA for Means (RU)						
RF	3	0.046771	0.046771	0.015590	8.19	0.059
SC	3	0.602995	0.602995	0.200998	105.56	0.002
SL	3	0.010807	0.010807	0.003602	1.89	0.307
SR	3	0.023346	0.023346	0.007782	4.09	0.139
Residual Error	3	0.005712	0.005712	0.001904		
Total	15	0.689632				

9.4.2 Normal probability plot (RF)

The main assumptions for using ANOVA is that the sample data used should be normally distributed and have equal variances. The normality of the data can be checked with a normal probability plot of residuals. If the plot is a straight line then it confirms that the distribution of residuals is normal. The variance is constant if the residuals versus fitted value plot do not follow any pattern. Figures 9.13, 9.15 and 9.17 show the normality plot of the residuals for MST, WIP and RU respectively. It is observed from the plot that the residuals follow the normal distribution. Figure 9.14, 9.16 and 9.18 are drawn between the residuals and fitted value for the MST, WIP and RU respectively that does not shows any pattern. Thus the assumptions of normality and constant variance are satisfied.

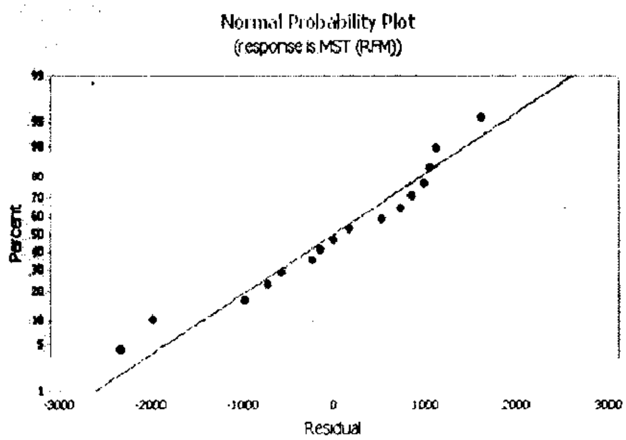


Figure 9.13: Normality plot of residuals for MST (RF)

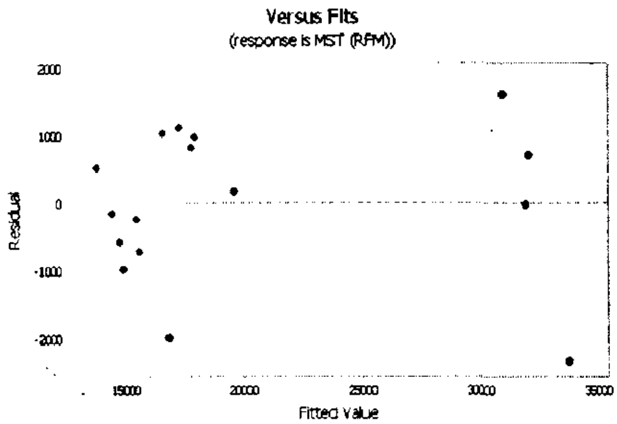


Figure 9.14: Residuals versus fitted values plot for MST (RF)

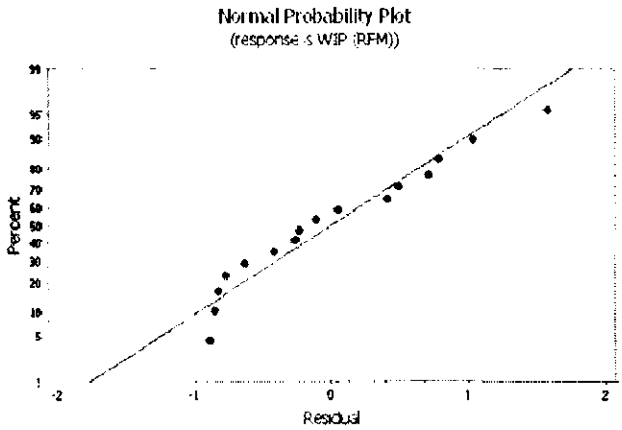


Figure 9.15: Normality plot of residuals for WIP (RF)

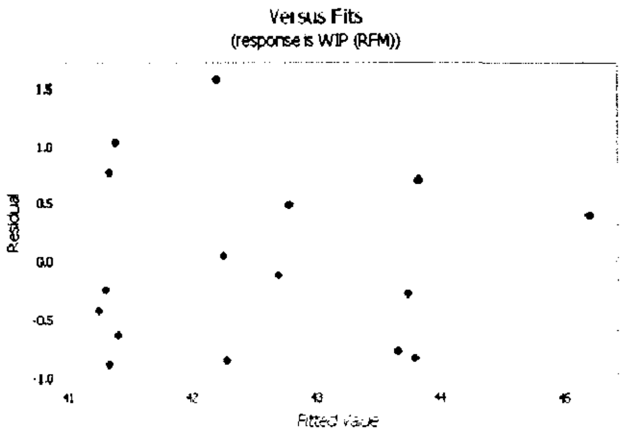


Figure 9.16: Residuals versus fitted values plot for WIP (RF)

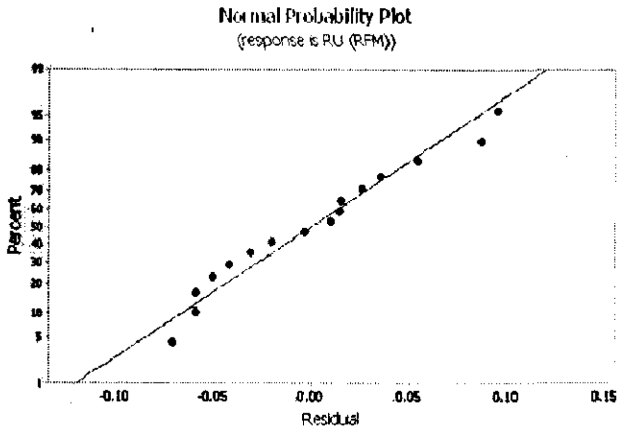


Figure 9.17: Normality plot of residuals for RU (RF)

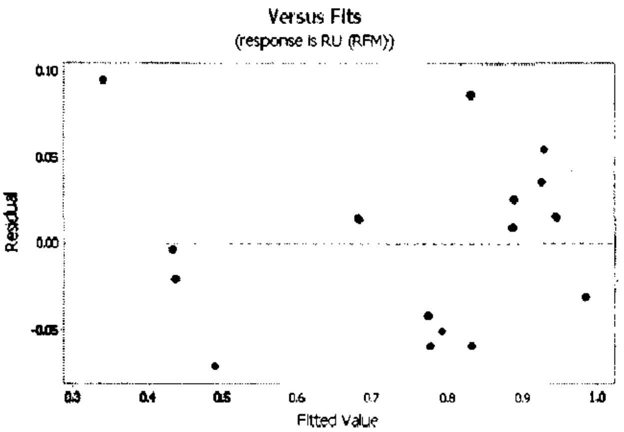


Figure 9.18: Residuals versus fitted values plot for RU (RF)

9.4.3 Confirmation experiment (RF)

Based on the S/N ratio and ANOVA analysis, the optimal levels of all the control factors are identified. As mentioned before the optimum setting of parameters for MST under RF is RF3 SC4 SL1 SR1, for WIP the optimum level is RF2 SC2 SL4 SR2 and for RU, RF0 SC1 SL4 SR3 is the optimum level in the given condition. The confirmation experiment is the final step of a design of experiment. Its objective was to verify the optimum conditions suggested by the matrix experiment. The confirmation experiment was performed by conducting a test with optimal settings of the factors and the levels which were previously evaluated. The predicted value of S/N ratio at optimum level (η_o) was calculated by the relation (9.2).

9.4.3.1:S/N ratio calculation at optimal level (RF)

The above mentioned procedure is followed for computing the optimum S/N ratio and the expected performance value for MST, WIP and RU. The results obtained are tabulated in the table 9.11 given below.

Table 9.11: Results of confirmation experiment (RF)

	Optimal parameters for routing flexibility	
	Predicted	Experimental
Level	**RF3 SC4 SL1 SR1**	**RF3 SC4 SL1 SR1**
MST	12489.78	13963.16
S/N value	-81.9311	-82.89
Level	**RF2 SC2 SL4 SR2**	**RF2 SC2 SL4 SR2**
WIP	39.97	41.8
S/N value	-32.036	-32.42
Level	**RF0 SC1 SL4 SR3**	**RF0 SC1 SL4 SR3**
RU	0.346	0.431
S/N value	9.21	7.31

In this work it has been found that the best factor level combinations under MST is **RF3, SC4, SL1** and **SR1.This** can be easily interpreted as the routing flexibility level 4, the system capacity 120, load fully balanced (LFB), and the sequencing rule as FCFS, while **RF2, SC2, SL4 and SR2**, which can be easily interpreted as the routing flexibility level 3, the system capacity 60, load balanced on machine and unbalanced processing time (LBMUPT), and the sequencing rule as SPT is the best combination for WIP. Where as in case of RU the best combination is **RF0, SC1, SL4 and SR3**, which means that routing flexibility level is 1, the system capacity is 30, system load condition is, load balanced on machine and unbalanced processing time (LBMUPT), and the sequencing rule is HPT.

9.5 Experimental results of SFMS with AGVs

With the help of table 9.1, table 9.12 is developed for Taguchi's design of experiment when the system is operating under AGV. The results obtained are shown in table 9.13.

Table 9.12: Physical and coded values of decisions factors for Taguchi's design of experiment (AGV)

Symbols	Factors	Levels			
	Coding- Orthogonal array	1	2	3	4
NAGV	Number of AGV	1	2	3	4
VAGV	Velocity of AGV (m/s)	2	4	6	8
SC	System load conditions	30	60	90	120
SR	Sequencing rules	FCFS	SPT	HPT	LCFS

Table 9.13: Orthogonal array $L_{16}(4^4)$ with experimental results and calculated S/N ratios (AGV)

Exp. No.	No. AGV	Vel. AGV	SC	SR	MST /min.	S/N ratio /(dB)	WIP (%)	S/N ratio /(dB)	RU (%)	RU ratio /(dB)
1	1	1	1	1	98363	-99.85	48.83	-33.77	0.13	17.27
2	1	2	2	2	81526	-98.22	49.02	-33.80	0.16	15.51
3	1	3	3	3	75879	-97.60	49.53	-33.89	0.18	14.84
4	1	4	4	4	73118	-97.28	50.01	-33.98	0.18	14.64
5	2	1	2	3	49239	-93.84	47.7	-33.57	0.27	11.07
6	2	2	1	4	43427	-92.75	46.60	-33.36	0.30	10.27
7	2	3	4	1	38069	-91.61	48.17	-33.65	0.34	9.36
8	2	4	3	2	36688	-91.29	47.62	-33.55	0.37	8.57
9	3	1	3	4	32891	-90.34	46.79	-33.40	0.39	8.03
10	3	2	4	3	27454	-88.77	46.45	-33.34	0.49	6.03
11	3	3	1	2	33549	-90.51	45.59	-33.17	0.40	7.78
12	3	4	2	1	25210	-88.03	44.92	-33.05	0.50	5.97
13	4	1	4	2	24767	-87.87	45.56	-33.17	0.55	5.10
14	4	2	3	1	20858	-86.38	44.43	-32.95	0.58	4.66
15	4	3	2	4	233994	-87.38	44.44	-32.95	0.57	4.80
16	4	4	1	3	32342	-90.19	44.99	-33.06	0.42	7.39

The next step is to identify the optimal factor combinations that generate the best system performance. According to the Taguchi experimental framework, the analysis of means (ANOM) can be used to achieve the best optimal factor combination.

9.5.1 Optimal factor combinations (AGV)

With reference to the ANOM, the m_{jk} values for SFMS with the three measuring parameters MST, WIP and RU are presented in Tables 9.14. The S/N ratio is used for the representation rather than the observed readings, so that the optimal levels for each factor can be represented by the maximum point in the graph shows in the figure 9.19, 9.20 and 9.21.

Table 9.14: Factor mean effects of matrix experiment (AGV)

Factor level Main effect	Applicable formula	MST S/N (α) ratio (dB)	WIP S/N (α) ratio (dB)	RU S/N (α) ratio (dB)
m_{SF0}	(α1+ α2+ α3+ α4)/4	-98.24	-33.86	15.57
m_{SF1}	(α5+ α6+ α7+ α8)/4	-92.37	-33.53	9.82
m_{SF2}	(α9+ α10+ α11+ α12)/4	-89.41	-33.24	6.95
m_{SF3}	(α13+ α14+ α15+ α16)/4	-87.96	-33.03	5.49
m_{SC1}	(α1+ α5+ α9+ α13)/4	-92.98	-33.48	10.37
m_{SC2}	(α2+ α6+ α10+ α14)/4	-91.53	-33.36	9.12
m_{SC3}	(α3+ α7+ α11+ α15)/4	-91.77	-33.42	9.19
m_{SC4}	(α4+ α8+ α12+ α16)/4	-91.69	-33.41	9.14
m_{SL1}	(α1+ α6+ α11+ α16)/4	-93.33	-33.34	10.68
m_{SL2}	(α2+ α5+ α12+ α15)/4	-91.87	-33.34	9.34
m_{SL3}	(α3+ α8+ α9+ α14)/4	-91.40	-33.45	9.03
m_{SL4}	(α4+ α7+ α10+ α13)/4	-91.38	-33.53	8.78
m_{SR1}	(α1+ α7+ α12+ α14)/4	-91.47	-33.35	9.32
m_{SR2}	(α2+ α8+ α11+ α13)/4	-91.97	-33.42	9.24
m_{SR3}	(α3+ α5+ α10+ α16)/4	-92.60	-33.46	9.83
m_{SR4}	(α4+ α6+ α9+ α15)/4	-91.94	-33.42	9.44

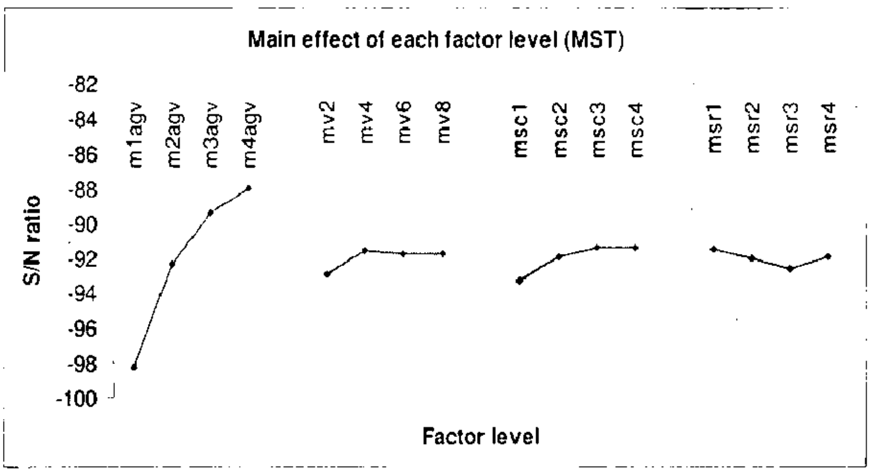


Figure 9.19: Main effects of each factor level with reference to MST (AGV)

With reference to Figure 9.19, which shows the main effects of each factor level, it can be found that the best factor level combination under the measurement of makespan is **4AGV,** V4, SC4 and SR1, which can be easily interpreted as the number of AGVs are 4, the velocity of AGV is 4 m/s, the system capacity 120, and the sequencing rule as FCFS.

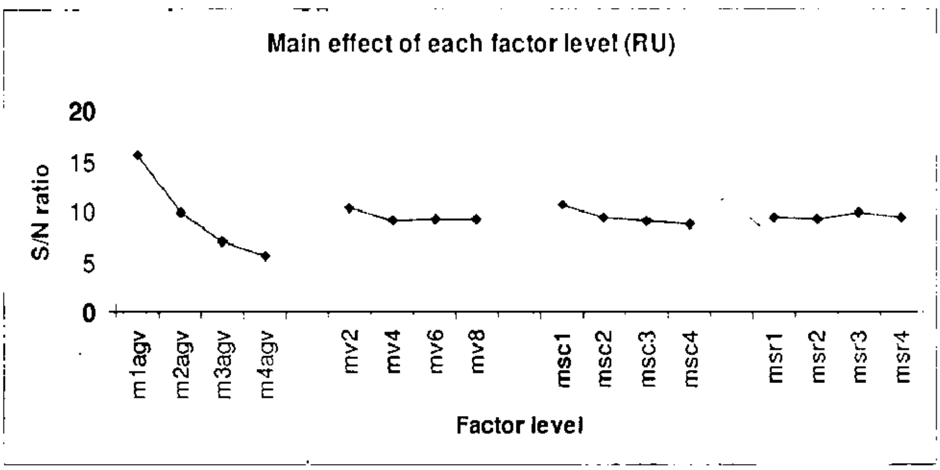


Figure 9.20: Main effects of each factor level with reference to RU (AGV)

Figure 9.20 shows the main effects of each factor level, it can be found that the best factor level combination under the measurement of resource utilization is 1AGV, V2, SC1 and SR3, which can be easily interpreted as the number of AGV is 1, the velocity of AGV is 2 m/s, the system capacity 30, and the sequencing rule as HPT.

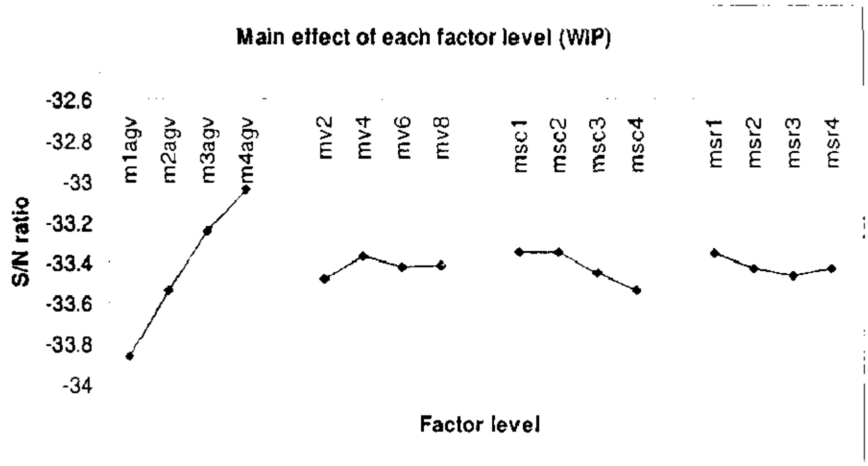


Figure 9.21: Main effects of each factor level with reference to WIP (AGV)

Figure 9.21 shows the main effects of each factor level, it can be found that the best factor level combination under the measurement of work-in-process is 4AGV, V4, SC1 and SR1, which can be easily interpreted as the number of AGVs are 4, the velocity of AGV is 4 m/s, the system capacity 30, and the sequencing rule as FCFS.

In addition to the above analysis, the relative significance of different factors on the system is also very important to discuss. In this connection, the impact of factors acting on the system is recognized with the analysis of variance (ANOVA). The simulation results of the MST, WIP and RU of the system (see Tables 9.13) are chosen for constructing the ANOVA table (Table 9.15). According to table 9.15, the F-value of the number of AGVs is the highest at MST, RU and WIP while the sequencing rules are the least significant at all measures in the given models.

Table 9.15: ANOVA showing the simulation results of model at different outputs (AGV)

ANOVA for Means (MST)						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
NAGV	3	8053564247	8053564247	2684521416	178.08	0.001
VAGV	3	230884274	230884274	76961425	5.11	0.107
SC	3	306645562	306645562	102215187	6.78	0.075
SR	3	22795453	22795453	7598484	0.50	0.706
Residual Error	3	45224719	45224719	15074906		
Total	15	8659114253				
ANOVA for Means (WIP)						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
NAGV	3	45.9249	45.9249	15.3083	62.66	0.003
VEL.	3	0.7169	0.7169	0.2390	0.98	0.507
SC	3	3.0036	3.0036	1.0012	4.10	0.138
SR	3	0.7001	0.7001	0.2334	0.96	0.515
Error	3	0.7329	0.7329	0.2443		
Total	15	51.0784				
ANOVA for Means (RU)						
NAGV	3	0.308313	0.308313	0.102771	32.48	0.009
VAGV	3	0.004790	0.004790	0.001597	0.50	0.706
SC	3	0.013949	0.013949	0.004650	1.47	0.380
SR	3	0.004164	0.004164	0.001388	0.44	0.742
Residual Error	3	0.009491	0.009491	0.003164		
Total	15	0.340707				

9.5.2 Normal probability plot (AGV)

The main assumptions for using ANOVA was that the sample data used should be normally distributed and have equal variances. The normality of the data can be checked with a normal probability plot of residuals. If the plot is a straight line then it confirms that the distribution of residuals is normal. The variance is if the residuals versus fitted value plot do not follow any pattern. Figures 9.22, 9.24 and 9.26 show the normality plot of the residuals for MST, WIP and RU respectively. It is observed from the plot that the residuals follow the normal distribution. Figure 9.23, 9.25 and 9.27 are drawn between the residuals and fitted value for the MST, WIP and RU respectively that does not shows any pattern. Thus the assumptions of normality and constant variance are satisfied.

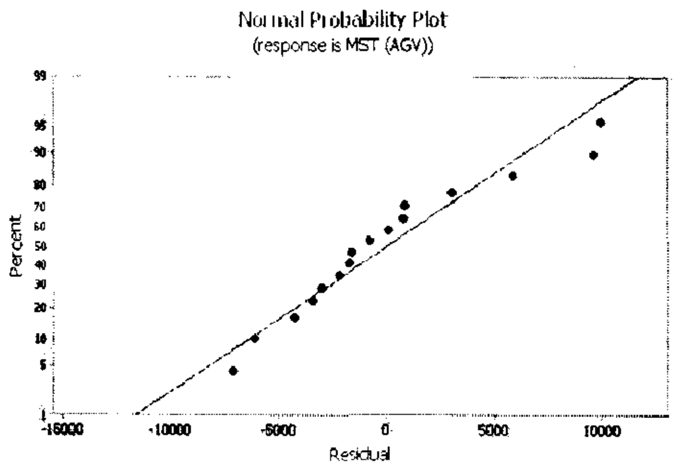


Figure 9.22: Normality plot of residuals for MST

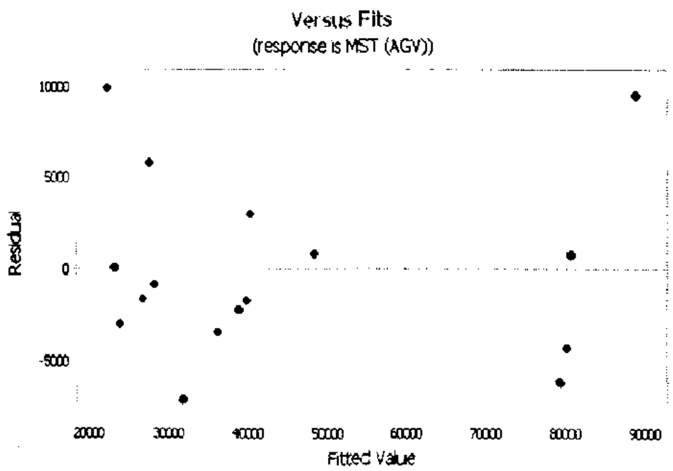


Figure 9.23: Residuals versus fitted values plot for MST

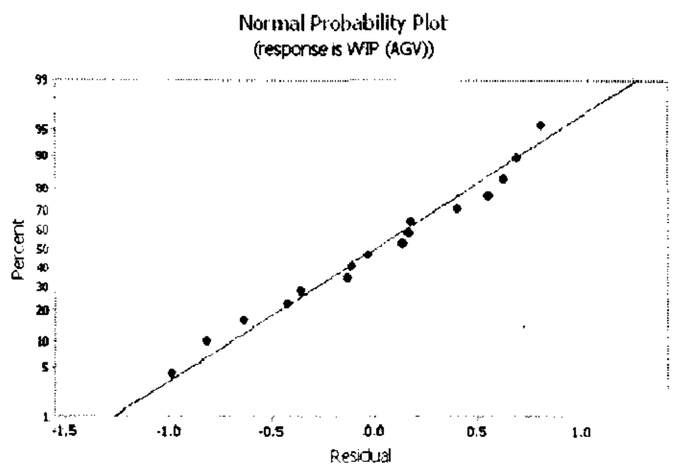


Figure 9.24: Normality plot of residuals for WIP

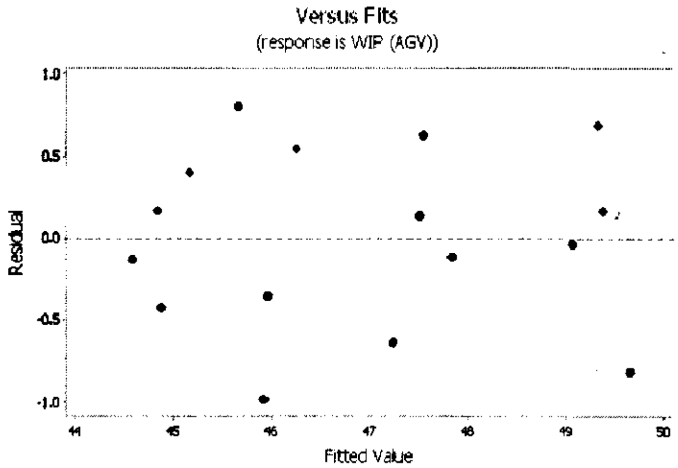


Figure 9.25: Residuals versus fitted values plot for WIP

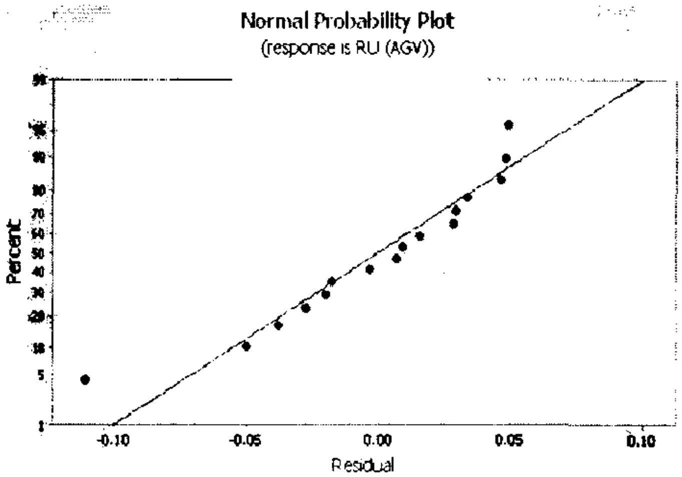


Figure 9.26: Normality plot of residuals for RU

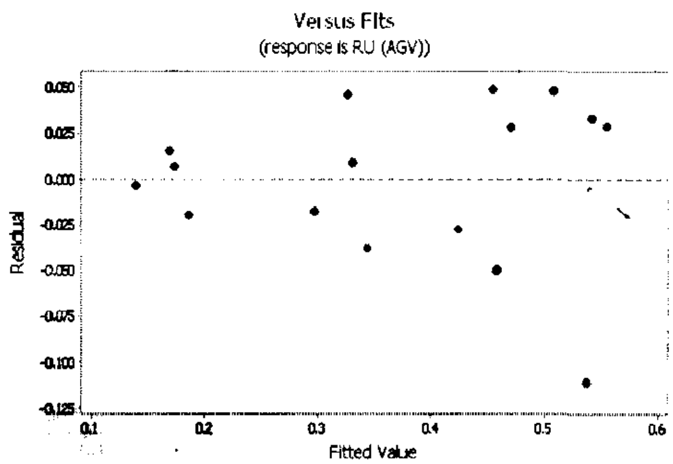


Figure 9.27: Residuals versus fitted values plot for RU

9.5.3: Confirmation experiment (AGV)

Based of the S/N ratio and ANOVA analysis, the optimal levels of all the control factors are identified. As mentioned before the optimum setting of parameters for MST with AGVs is **4AGV, V4, SC4** and **SR1**, for WIP the optimum level is **4AGV, V4, SC1** and **SR1** and for RU **1AGV, V2, SC1** and **SR3** is the optimum level in the given condition. The confirmation experiment is the final step of a design of experiment. Its objective is to verify the optimum conditions suggested by the matrix experiment. The confirmation experiment was performed by conducting a test with optimal settings of the factors and the levels which were previously evaluated. The predicted value of S/N ratio at optimum level (η_o) is calculated by the relation (9.2).

9.5.3.1:S/N ratio calculation at optimal level

The above mentioned procedure was followed for computing the optimum S/N ratio and the expected performance value for MST, WIP and RU. The results obtained are tabulated in the table given below.

Table 9.16: Results of confirmation experiment (AGV)

	Optimal parameters with AGVs	
	Predicted	Experimental
Level	**4AGV V4 SC4 SR1**	**4AGV V4 SC4 SR1**
Makespan	20820.9	20728.7
S/N value	-86.37	-86.33
Level	**4AGV V4 SC1 SR1**	**4AGV V4 SC1 SR1**
Work-in-process	43.75	45.162
S/N value	-32.82	-33.10
Level	**1AGV V2 SC1 SR3**	**1AGV V2 SC1 SR3**
Resource utilization	0.124	0.139
S/N value	18.07	17.139

Taguchi's experiment design pattern provides us with a fast way to study the behavior of some control factors in a SFMS. It has been found that the best factor level combination under the measurement of MST is **4AGV, V4, SC4 and SR1**, which can be easily interpreted as the number of AGVs are 4, the velocity of AGV is 4 m/s, the system capacity 120, and the sequencing rule as FCFS where as in case of RU the best combination is **1AGV, V2, SC1 and SR3,** which can be easily interpreted as the number of AGVs is 1, the velocity of AGV is 2 m/s, the system capacity 30, and the sequencing rule as HPT, while **4AGV, V4, SC1 and SR1** is the best combination for WIP measurement, which can be easily interpreted as the number of AGVs is 4, the velocity of AGV is 4 m/s, the system capacity 30, and the sequencing rule as FCFS.

9.6 Experimental results of SFMS with combined flexibility (SF3RF1)

With the help of table 9.1, table 9.17 is developed for Taguchi's design of experiment when the system is operating under combined sequencing and routing flexibility. The results obtained are shown in table 9.13.

Table 9.17: Physical and coded values of decisions factors for Taguchi's design of experiment (CF)

Symbols	Factors	Levels		
	Coding- Orthogonal array	1	2	3
MF	Manufacturing flexibility	SF3	RF1	SF3RF1
SL	System load conditions	LUB	LFB	LUMBPT
SR	Sequencing rules	FCFS	SPT	HPT

Table 9.18: Orthogonal array $L_9(3^3)$ with experimental results and calculated S/N ratios (AGV)

Exp. No.	SF	SR	SL	MST	S/N ratio **MST** (dB)	WIP	S/N ratio WIP (dB)	RU	S/N ratio RU (dB)
1	SF3	FCFS	LUB	16734	-84.47	58.008	-35.26	0.8176	1.749
2	SF3	SPT	LFB	16542	-84.37	55.454	-34.87	0.8215	1.707
3	SF3	HPT	LUMBPT	16738	-84.47	57.414	-35.18	0.8126	1.802
4	RF1	FCFS	LFB	14201	-83.04	41.560	-32.37	0.9600	0.354
5	RF1	SPT	LUMBPT	14142	-83.01	41.428	-32.34	0.9624	0.332
6	RF1	HPT	LUB	15143	-83.60	41.802	-32.42	0.9054	0.863
7	SF3RF1	FCFS	LUMBPT	13672	-82.71	57.472	-35.18	0.9937	0.054
8	SF3RF1	SPT	LUB	13883	-82.85	54.588	-34.74	0.9886	0.099
9	SF3RF1	HPT	LFB	13812	-82.80	56.465	-35.03	0.9864	0.118

The next step is to identify the optimal factor combinations that generate the best system performance. According to the Taguchi experimental framework, the analysis of means (ANOM) can be used to achieve the best optimal factor combination.

9.6.1 Optimal factor combinations (AGV)

With reference to the ANOM, the m_{jk} values for SFMS with the three measuring parameters MST, WIP and RU are presented in Table 9.19. The S/N ratio was used for the representation rather than the observed readings so that the optimal levels for each factor can be represented by the maximum point in the graph shows in the figure 9.28, 9.29 and 9.30.

Table 9.19: Factor mean effects of matrix experiment (CF)

Factor level Main effect	Applicable formula	MST S/N (α) ratio (dB)	WIP S/N (α) ratio (dB)	RU S/N (α) ratio (dB)
SF3	α1+ α2+ α3	-84.44	-35.11	-1.753
RF1	α 4+ α5+ α6	-83.22	-32.38	-0.516
SF3RF1	α 7+ α8+ α9	-82.79	-34.99	-0.091
FCFS	α1+ α4+ α7	-83.41	-34.28	-0.719
SPT	α 2+ α5+ α8	-83.41	-33.99	-0.713
HPT	α 3+ α6+ α9	-83.63	-34.21	-0.928
LUB	α1+ α6+ α8	-83.64	-34.15	-0.904
LFB	α 2+ α4+ α9	-83.41	-34.10	-0.727
LUMBPT	α 3+ α5+ α7	-83.40	-34.24	-0.730

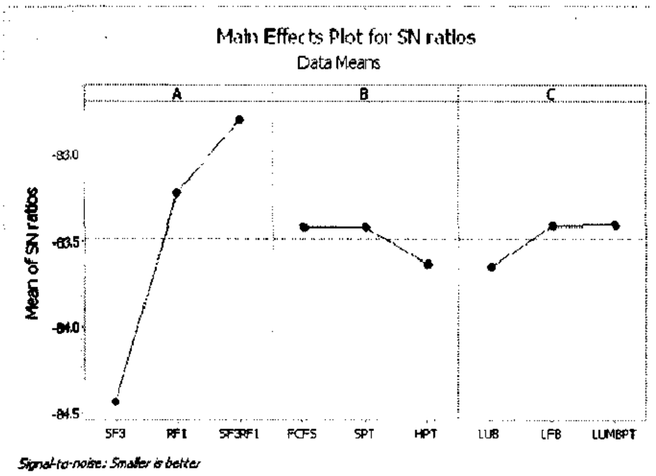


Figure 9.28: Main effects of each factor level (MST)

Figure 9.28, which shows the main effects of each factor level, it can be found that the best factor level combination under the measurement of make-span is SF3RF1, FCFS and LUMBPT, which can be easily interpreted as the combined flexibility, first-cum-first serve and load unbalanced on machine and balanced processing time.

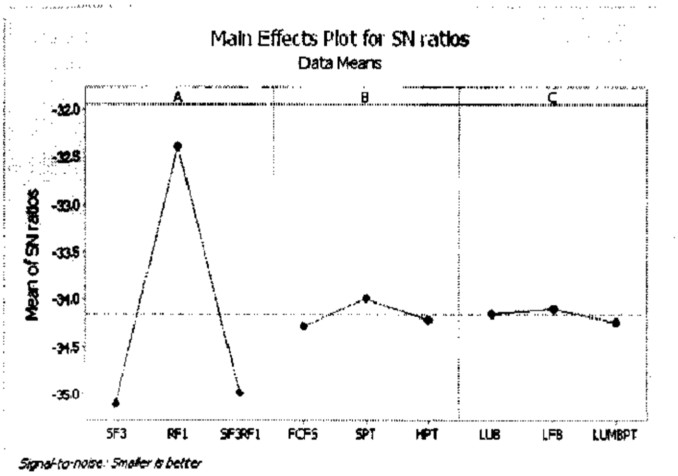


Figure 9.29: Main effects of each factor level (WIP)

Figure 9.29 shows the main effects of each factor level, it can be found that the best factor level combination under WIP is RF1, SPT and LFB, which can be easily interpreted as the routing flexibility, the sequencing rule as shortest process time and load fully balanced (LFB).

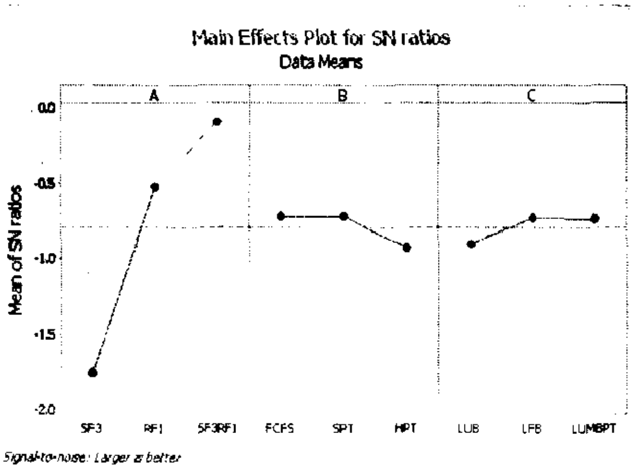


Figure 9.30: Main effects of each factor level (RU)

Figure 9.30 shows the main effects of each factor level, it can be found that the best factor level combination under the measurement of resource utilization is SF3RF1, FCFS and LFB, which can be easily interpreted as the combined flexibility, sequencing rules as first-cum-first serve and system load condition is load fully balanced.

In addition to the above analysis, the relative significance of different factors on the system is also very important to discuss. The relative significance of different factors on the system is known by performing ANOVA. The simulation results of the MST, WIP and RU of the system (see Table 9.18) are chosen for constructing the ANOVA table (table 9.20). According to Table 9.20, the F-value of the SF3 is the highest at MST, WIP and RU measure. Whereas the F value is lower at SF3RF1 for WIP and RU while it is minimum at RF3 for MST.

Table 9.20: ANOVA showing the simulation results of the model at different outputs (CF)

ANOVA for Means (MST)					
Source	**DF**	**Adj SS**	**Adj MS**	**F**	**P**
CF	2	13541728	6770864	162.12	0.006
SR	2	272097	136048	3.26	0.235
SL	2	323478	161739	3.87	0.205
Residual Error	2	83527	41763		
Total	8	14220830			
ANOVA for Means (WIP)					
Source	**DF**	**Adj SS**	**Adj MS**	**F**	**P**
CF	2	449.133	224.566	492.57	0.002
SR	2	5.623	2.811	6.17	0.140
SL	2	1.395	0.697	1.53	0.395
Residual Error	2	0.912	0.456		
Total	8	457.062			
ANOVA for Means (RU)					
Source	**DF**	**Adj SS**	**Adj MS**	**F**	**P**
CF	2	0.047621	0.023811	113.59	0.009
SR	2	0.001013	0.000506	2.42	0.293
SL	2	0.000715	0.000357	1.70	0.370
Residual Error	2	0.000419	0.000210		
Total	8	0.049768			

9.6.2: Normal probability plot (CF)

The main assumptions for using ANOVA is that the sample data used should be normally distributed and have equal variances. The normality of the data can be checked with a normal probability plot of residuals. If the plot is a straight line then it confirms that the distribution of residuals is normal. The variance is if the residuals versus fitted value plot do not follow any pattern. Figures 9.31, 9.33 and 9.35 show the normality plot of the residuals for make-span, work-in-process and resource utilization respectively. It is observed from the plot that the residuals follow the normal distribution. Figure 9.32, 9.34 and 9.36 are drawn between the residuals and fitted value for the make-span, work-in-process and resource utilization respectively that does not shows any pattern. Thus the assumptions of normality and constant variance are satisfied.

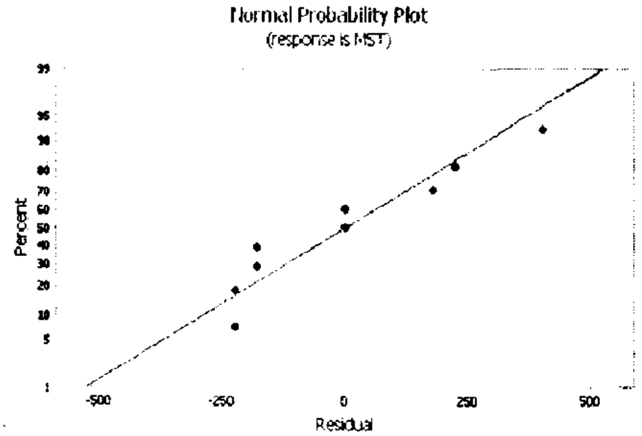


Figure 9.31: Normality plot of residuals (MST)

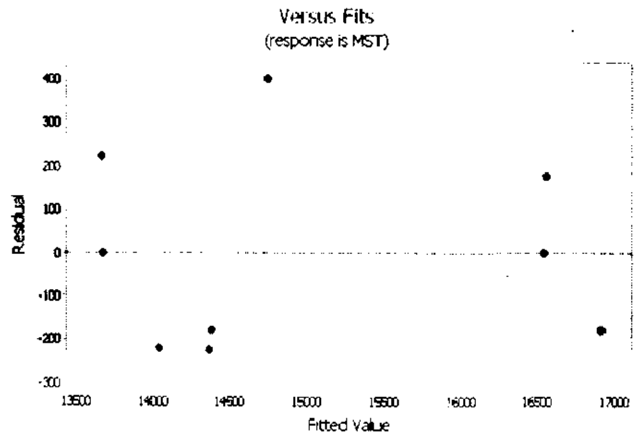


Figure 9.32: Residuals versus fitted values (MST)

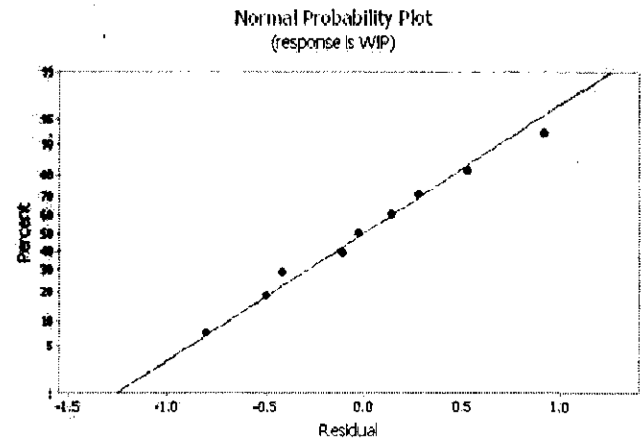


Figure 9.33: Normality plot of residuals (WIP)

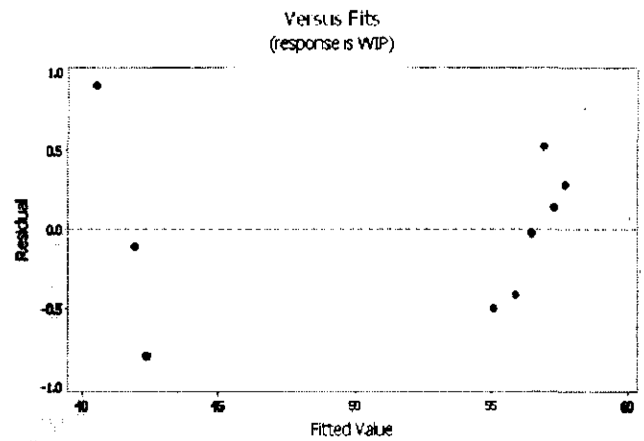


Figure 9.34: Residuals versus fitted values (WIP)

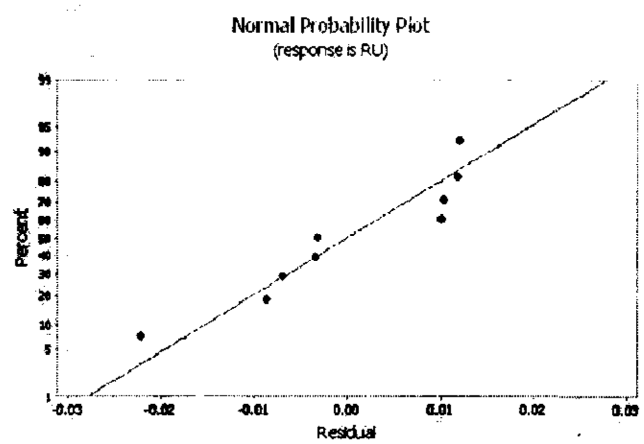


Figure 9.35: Normality plot of residuals (RU)

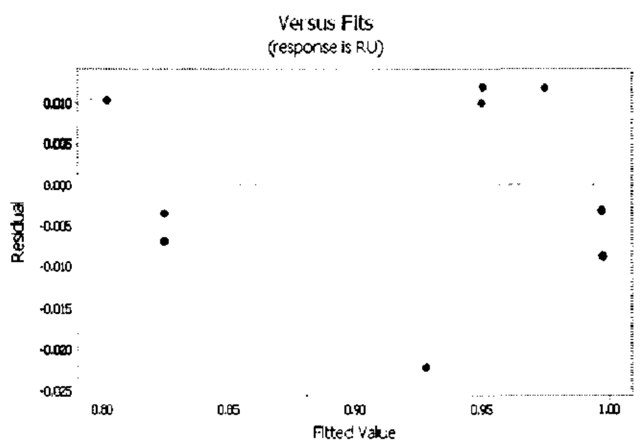


Figure 9.36: Residuals versus fitted values (RU)

9.6.3: Confirmation experiment (CR)

On the basis of S/N ratio and ANOVA analysis, the optimal levels of all the control factors are identified. As mentioned before the optimum setting of parameters for make-span under combined flexibility is SF3RF1, FCFS and LUMBPT. The confirmation experiment is the final step of a design of experiment. Its objective is to verify the optimum conditions suggested by the matrix experiment. The confirmation experiment is performed by conducting a test with optimal settings of the factors and the levels previously evaluated. The predicted value of S/N ratio at optimum level (η_o) is calculated by the relation (9.2).

9.6.3.1 :S/N ratio calculation at optimal level

The above mentioned procedure is followed for computing the optimum S/N ratio and the expected performance value for make-span, work-in-process and resource utilization. The results obtained are tabulated in the table given below.

Table 9.21: Results of confirmation experiment (CF)

	Optimal parameters for sequencing flexibility	
	Prediction	Experimental
Level	**SF3RF1 FCFS LUMBPT**	**SF3RF1 FCFS LUMBPT**
Make-span	14893.6	13672
S/N ratio	-83.46	-82.68
Level	**RF1 SPT LFB**	**RF1 SPT LFB**
Work-in-process	51.010	40.32
S/N ratio	-34.15	-32.10
Level	**SF3RF1 FCFS LFB**	**SF3RF1 FCFS LFB**
Resource utilization	1.094	0.9930
S/N ratio	0.7858	0.0603

Taguchi's experiment design pattern provides us with a fast way to study the behavior of some control factors in a flexible manufacturing system. It has been found that the best factor level combination under MST are SF3RF1, FCFS and LUMBPT where as in case of WIP the best combinations are RF1, SPT and LFB, while SF3RF1, FCFS and LFB is the best combinations for RU.

Chapter 10

Conclusion and Scope for Future Work

10.1 Introduction

This work is aimed to enrich a research theme focused on manufacturing system under stochastic environment in a flexibility context. It is characterized by a focus to model a stochastic flexible manufacturing system involving various decisions i.e. design decisions, planning decisions and control decisions. The design decision comprises of manufacturing flexibility i.e. sequencing flexibility (SF0, SF1, SF2 and SF3), routing flexibility (RF0, RF1, RF2 and RF3), number of AGVs (1, 2, 3 and 4) and buffer size (5, 10, 15 and 20) where as the planning decision covers system load (LUB, LFB, LUMBPT and LBMUPT) and system configuration (6 machine with dedicated input buffer) while control decision covers dispatching rule (MINQ), sequencing rule (FCFS, SPT, HPT and LCFS) and AGV velocity (2, 4, 6 and 8 m/s). The study uses make-span, work-in-process and resource utilization as performance measures to study the impact of different decisions. Thus the main focus of this study was on the interaction between various decisions in order to control the part flow effectively through the manufacturing system.

The role of flexibility at the operational levels is to ensure that each decision points have a set of alternative options. The role of control decisions is to help in the selection of most optimum solutions. This shows what is considered as the exploitation of flexibility at operational levels. This thesis enriched the above research themes envisioned by Sethi and Sathi (1990), Rachamadugu et al. (1993), Wadhwa and Rao (2004), Ali and Wadhwa (2010). A salient contribution of this effort is in adopting different system configurations with stochastic environment based on the manufacturing flexibility, system capacity, number of AGVs and AGV velocity. On the basis of these factors we developed three manufacturing systems i.e. sequencing flexibility model, routing flexibility model, AGV model and combined flexibility model. This thesis is a concerted research effort to enrich the SFMS by addressing some important research issues and their industrial implications.

In this chapter, we state the key conclusions arising out of this thesis. Then, we highlight the useful research contributions. Finally, the study limitations along with the scope for future work are discussed.

10.2 Conclusions

The detailed conclusions are given in each chapter based on the results analysis and discussions. In this section, we present some key conclusions regarding sample SFMS studied.

1. In the assessing flexible manufacturing system, design, planning and control decisions are considered as the important dimensions of a SFMS framework that assists the manufacturing flexibility under stochastic environment.
2. From the literature review we find that there is a need to enrich flexibility under stochastic environment. So far this is an attempt to contribute to this domain with a focus on the design, planning, and control decisions within a discrete part manufacturing system.
3. Here we focused on the design, planning and control decisions needed for phased development of FMS under stochastic environment. Design decisions include manufacturing flexibility, buffer size and number of

AGVs. Planning decisions include system load conditions, system configuration and batch size. Control decisions include sequencing and dispatching rules of parts in the system.

4. The developed framework of SFMS is based on GRAI methodology, which is based on the information and decision based control system.

5. A simulation model of SFMS has been developed in ARENA that can assist for modeling and simulation of different design, planning and control decisions in respect to shop floor under stochastic environment.

6. From the series of experiments conducted with sequencing flexibility, we observed that that the performance of SFMS improved with the increase of sequencing flexibility in most of the combinations planning and control decisions. Among the system load conditions LFB is found to be the best. Further, it is seen that the sequencing rules at the queue also has some impact on the performance of the system. It is found that this impact is more at lower level of sequencing flexibility because the formation of queue is more likely at lower level of sequencing flexibility. Hence, from the above discussion the sequencing rule FCFS has the best performance among the four selected sequencing rules.

7. The findings of the set experiments conducted with routing flexibility shows that the performance of SFMS improved with the increase of routing flexibility in all of the combinations but this increase of the performance is more significant when the SFMS is shifted from RF0 to RF1. In this study we found that sequencing rule SPT has the best

performance in most of the combinations. Further, it is concluded that the sequencing rules at the queue also has some impact on the performance of the system. It is found that this impact is more at lower level of routing flexibility because the formation of queue is more likely at lower level of routing flexibility.

8. When the experiments are conducted with AGVs it is observed that the performance of the system has improved with the increase in the number of AGVs as well as with the increase of AGV velocity in all of the combinations. It is found that the increase in the performance is more when the SFMS is shifted from 1 AGV to 2 AGVs. From the results it was found that the AGV velocity also has an impact on the performance measures but this effect is more visible at higher number of AGVs in compare to the less number of AGVs used in the SFMS.

9. From the results obtained after conducting the experiments with combined sequencing and routing flexibility it is found that there is a positive effect of combined effect of these flexibility on the system performance. The results are drawn between the percentage gain in the performance measures and other factors of the system. We found that there is a significant gain with the addition of another type of manufacturing flexibility in the existing manufacturing flexible system. This gain is about 20% in case of MST when we add routing flexibility in an existing sequencing flexibility and 17% gain in case of resource utilization while

there is no significant response on work-in-process in most of the conditions.

10. After performing full factorial experimentation we applied the Taguchi methods of design of experiment to study a number of factors at different levels. This includes selecting the suitable orthogonal array, assigning the factors and their interactions and the results were analyzed by using analysis of variance (ANOVA) and also check the assumptions considered in the ANOVA before drawing the conclusions.

11. The data normality is checked with a normal probability plot of residuals. As we find that the normality plot of residuals is having a straight line. Therefore we conclude that the sample data used for ANOVA is normally distributed and have equal variances.

12. The constant variance assumption is also checked by the residuals versus fitted value plot. We found that the residuals versus fitted value plot does not follow any pattern, therefore we can say that the constant variance assumption is satisfied.

13. Finally on the bases of the S/N ratio and ANOVA analysis, the optimal levels of all the control factors are identified and the confirmation experiment was performed by conducting a test with optimal settings of the factors and the levels previously evaluated. And then the predicted and experimental results were presented in a tabulated form. Therefore we conclude that the Taguchi method for design of experiment gives quite fair results as close to the full factorial experimentation.

10.4 Contribution of present research work

This study is an overall holistic approach to identify the suitable combination of the different levels of design, planning and control decisions. The implementation of the full FMS in an industry needs huge investments therefore it is difficult to allow any wrong decision in any of the manufacturing industry. Selection of any of the parameter needs a very careful decision because some of the parameters either have very little or some time counter productive effects. This is an attempt to help the researchers and practitioners to have an improved understanding on each of these options related to SFMS. Following are the salient contributions:

- This thesis lays down original conceptualization of a framework of SFMS to assist FMS in stochastic environment. It will be an access to the proposed framework of SFMS that can be used at different operational conditions in real like environment.
- This work is an attempt to help researchers and practitioners to have batter understanding of design, planning and control of FMS in stochastic environment.
- The results of the routing flexibility system configuration, the initial level of routing flexibility offers significant benefits whereas further increases in the routing flexibility offers marginal benefits and sometimes have negative effects on the system performance.

- There is positive impact of AGVs on the system, which reduces about 50% of the make-span when we introduce one more AGV in the initial system. And then further increase of AGVs reduces the rate of improvement in the system.
- The velocity of the AGVs is also having a positive impact on the system but this impact is more visible at higher number of AGV use in compare to the less number of AGV.
- Simulation of the SFMS also shows that the buffer capacity has an important factor to run the system effectively and efficiently without blocking.
- The use of simulation technique gives us a platform for modeling a complex system with its visual animation capabilities. It also provides an efficient means of learning, experimenting and analyzing complex system such a SFMS and help in achieving improved performance.

10.5 Limitation of the present work

Following are some of the key limitations of the present study that indicates the related scope for future work also.

- This work modeled few cases under design, planning and control decisions. A broader spectrum of data set, with more variety of parts and machines needs to be taken into consideration to aid the practitioners take judicious decision regarding the implementation of FMS under stochastic manufacturing environment.
- The conclusions based on the analysis of the simulation results need to be validated in the real life practical domain. Model verifications were carried out

with the inbuilt features of ARENA package and discussions with the professionals.

- This work is a relatively new effort dealing with the phased development of SFMS. The aim of our effort was conceptualization and development of a simulation demonstrative platform. The simulation models were built with some assumptions, which may not be fully practical to implement.
- We have considered identical machine without breakdowns. Machine breakdowns could be considered for further analysis of SFMS.
- Different form of cost was not included in the work. This may be included to know the trade-off between manufacturing flexibility and cost.

10.6 Scope of future work

Following are some of the issues that researchers can consider for future work:

- This work is based on a limited set of operating conditions for modeling stochastic flexible manufacturing system. Considering the shop floor, one can consider more part varieties, machines, operations, buffer capacity etc.
- In this work machine break down conditions is not considered. If considered this will add more uncertainty in the system.
- Some external changes such as cancellation of orders leading, to the scrapping of the specific operations on various parts, change in priorities etc. need to be considered.

- The synergy between more components of FMS i.e., Flexible Inspection System, Flexible Assembly System, Automated Storage and Retrieval System etc. can be exploited for further research.

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Table A4. System operating under UMLBPT condition

UMTBPT	M1	M2	M3	M4	M5	M6	
P1	33	25	35		18	25	**136**
P2		35	25	32	20	24	**136**
P3	40		24	30	22	20	**136**
P4		38	27	25	31	15	**136**
P5	55		23	16	17	25	**136**
P6		25	20	20	35	36	**136**
	128	**123**	**154**	**123**	**143**	**145**	*816*

Normal Distribution: Mean = 27.2
Stand. Deviation = 8.62

Appendex B

Figure B-1 Sequence of operations for SF0

	Operation 1	Operation 2	Operation 3	Operation 4	Operation 5
Part 1	M1	M2	M3	M5	M6
Part 2	M2	M3	M4	M5	M6
Part 3	M1	M2	M3	M4	M5
Part 4	M2	M3	M4	M5	M6
Part 5	M1	M3	M4	M5	M6
Part 6	M2	M3	M4	M5	M6

Table B-2 Sequence of operations for SF1

	Operation 1	Operation 2	Operation 3	Operation 4	Operation 5
Part 1	M1	M2	M3	M5	M6
Part 2	M2	M3	M4	M5	M6
Part 3	M1	M2	M4	M5	M6
Part 4	M2	M3	M4	M5	M6
Part 5	M1	M3	M4	M5	M6
Part 6	M2	M3	M4	M5	M6

Table B-3 Sequence of operations for SF2

	Operation 1	Operation 2	Operation 3	Operation 4	Operation 5
Part 1	M1	M2	M3	M5	M6
Part 2	M2	M3	M4	M5	M6
Part 3	M1	M2	M4	M5	M6
Part 4	M2	M3	M4	M5	M6
Part 5	M1	M3	M4	M5	M6
Part 6	M2	M3	M4	M5	M6

Table B-4 Sequence of operations for SF3

	Operation 1	Operation 2	Operation 3	Operation 4	Operation 5
Part 1	M1	M2	M3	M5	M6
Part 2	M2	M3	M4	M5	M6
Part 3	M1	M2	M3	M4	M5
Part 4	M2	M3	M4	M5	M6
Part 5	M1	M3	M4	M5	M6
Part 6	M2	M3	M4	M5	M6

Appendix C
Routing for Sequence of Operations

Table C-1 Routing for sequencing of operations for RF0.

RF0	O1	O2	O3	O4	O5
P1	M1	M2	M3	M5	M6
P2	M2	M3	M4	M5	M6
P3	M1	M3	M4	M5	M6
P4	M2	M3	M4	M5	M6
P5	M1	M3	M4	M5	M6
P6	M2	M3	M4	M5	M6

Table C-2 Routing for sequencing of operations for RF1

RF1	O1	O2	O3	O4	O5
P1	M1	M2	M3	M5	M6
	M3	M4	M5	M6	M2
P2	M2	M3	M4	M5	M6
	M4	M5	M6	M1	M2
P3	M1	M3	M4	M5	M6
	M5	M6	M1	M2	M3
P4	M2	M3	M4	M5	M6
	M6	M1	M2	M3	M4
P5	M1	M3	M4	M5	M6
	M2	M1	M3	M6	M5
P6	M2	M3	M4	M5	M6
	M3	M4	M5	M6	M1

Table C-3 Routing for sequencing of operations for RF2

RF2	O1	O2	O3	O4	O5
P1	M1 M3 M4	M2 M4 M1	M3 M5 M2	M5 M6 M3	M6 M2 M5
P2	M2 M4 M1	M3 M5 M4	M4 M6 M3	M5 M1 M2	M6 M2 M5
P3	M1 M5 M2	M3 M6 M4	M4 M1 M3	M5 M2 M1	M6 M3 M5
P4	M2 M6 M1	M3 M1 M5	M4 M2 M3	M5 M3 M4	M6 M4 M2
P5	M1 M2 M4	M3 M1 M2	M4 M3 M5	M5 M6 M3	M6 M5 M1
P6	M2 M3 M1	M3 M4 M2	M4 M5 M3	M5 M6 M4	M6 M1 M5

Table C-4 Routing for sequencing of operations for RF3

RF3	O1	O2	O3	O4	O5
P1	M1 M3 M4 M5	M2 M4 M1 M6	M3 M5 M2 M1	M5 M6 M3 M2	M6 M2 M5 M4
P2	M2 M4 M1 M5	M3 M5 M4 M1	M4 M6 M3 M2	M5 M1 M2 M3	M6 M2 M5 M4
P3	M1 M5 M2 M6	M3 M6 M4 M2	M4 M1 M3 M5	M5 M2 M1 M3	M6 M3 M5 M4
P4	M2 M6 M1 M4	M3 M1 M5 M6	M4 M2 M3 M1	M5 M3 M4 M2	M6 M4 M2 M3
P5	M1 M2 M4 M5	M3 M1 M2 M4	M4 M3 M5 M6	M5 M6 M3 M2	M6 M5 M1 M3
P6	M2 M3 M1 M4	M3 M4 M2 M5	M4 M5 M3 M6	M5 M6 M4 M1	M6 M1 M5 M2

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LIST OF PUBLICATIONS

Wasif Ullah Khan and Mohammed Ali, Effect of Sequencing Flexibility on the performance of Flexibility Enabled Manufacturing System, International Journal of Industrial and Systems Engineering (In press).

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